An Instrumented Pendulum System for Measuring Energy Absorption During Fracture Insult to Large Animal Joints in Vivo

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For systematic laboratory studies of bone fractures in general and intra-articular fractures in particular, it is often necessary to control for injury severity. Quantitatively, a parameter of primary interest in that regard is the energy absorbed during the injury event. For this purpose, a novel technique has been developed to measure energy absorption in experimental impaction. The specific application is for fracture insult to porcine hock (tibiotalar) joints in vivo, for which illustrative intra-operative data are reported. The instrumentation allowed for the measurement of the delivered kinetic energy and of the energy passed through the specimen during impaction. The energy absorbed by the specimen was calculated as the difference between those two values. A foam specimen validation study was first performed to compare the energy absorption measurements from the pendulum instrumentation versus the work of indentation performed by an MTS machine. Following validation, the pendulum apparatus was used to measure the energy absorbed during intra-articular fractures created in 14 minipig hock joints in vivo. The foam validation study showed close correspondence between the pendulum-measured energy absorption and MTS-performed work of indenta-

tion. In the survival animal series, the energy delivered ranged from 31.5 to 48.3 Js (41.3 ± 4.0 , mean $\pm$ s.d.) and the proportion of energy absorbed to energy delivered ranged from 44.2% to 64.7% ($53.6\% \pm 4.5\%$). The foam validation results support the reliability of the energy absorption measure provided by the instrumented pendulum system. Given that a very substantial proportion of delivered energy passed—unabsorbed—through the specimens, the energy absorption measure provided by this novel technique arguably provides better characterization of injury severity than is provided simply by energy delivery.
[DOI: 10.1115/1.4025113]

Introduction

Biomechanical impaction experiments have often been performed to study tissue and organ responses to injury (e.g., Refs. [1–5]). In the field of orthopedic biomechanics, fractures of bone are of particular interest. Clinically, the severity of fractures is often (subjectively) described in terms of the energy of the precipitating injury event [6]. Among fractures of bone, those involving the joint surface (intra-articular fractures (IAFs)) are especially challenging from an orthopedic management standpoint [7]. Besides fostering bony healing, treatment also aims to forestall posttraumatic osteoarthritis (PTOA), joint deterioration that arises from chronic loading abnormality of imprecisely reduced fractures and/or from acute insult of cartilage. To date, IAFs have received relatively little attention in controlled laboratory settings. Rather, most research on IAFs has involved either registry-based clinical studies [8–11] or laboratory animal or cadaveric models, where the insult of interest (e.g., osteotomy [12–15]) bears only limited similarity to an actual physiologic IAF event.

For systematic laboratory studies of bone fractures in general and IAFs in particular, it is necessary to control for injury severity. Quantitatively, a parameter of primary interest in that regard is the energy absorbed during the fracture event [16]. Normally, however, energy assessments in laboratory injury models have involved only the energy delivered to the specimen [1,2], rather than the energy actually absorbed in the injury.

This paper reports novel methodology for measuring the fracture energy absorbed in laboratory biomechanical impaction experiments. The specific implementation is in a testing system used to create IAFs in a large-animal survival model, the porcine hock joint [17]. The underlying concept, however, is generalizable to a wide variety of laboratory impaction experiments.

Methods

Impacts were delivered by a novel instrumented pendulum system (Fig. 1(a)), designed for survival animal studies and capable of delivering energy levels sufficient to fracture major weight-bearing joints in large species. The system, shown diagrammatically in Fig. 1(b), is compatible with operating room sterile field conditions required for survival studies. Employing the principle of the standard Charpy and Izod impact energy tests [18], energy delivery to the joint is modulated by controlling the release height of a pendulum. When using porcine (minipig) hock joints to model human tibial pilon fractures, the study animal's talus and tibia are suspended in appropriate apposition for creating fractures of the distal tibial articular surface, using a previously described purpose-designed bone-anchoring apparatus (Fig. 1(c)). To increase experimental reproducibility of fracture morphology, a subarticular surface stress-rising crack (saw cut) is employed [17]. The apparatus is mounted in series with a sled that can translate horizontally along low-friction linear bearings. Translation of the sled from the impact position is resisted by a linear compression spring placed between the sled and a fixed stop.

The instrumentation for energy absorption measurement is based on the concept that not all of the energy delivered by the

Contributed by the Bioengineering Division of ASME for publication in the JOURNAL OF BIOMECHANICAL ENGINEERING. Manuscript received March 3, 2013; final manuscript received June 26, 2013; accepted manuscript posted July 30, 2013; published online April 23, 2014. Assoc. Editor: Richard Neptune.

Fig. 1 The instrumented pendulum system is shown in (a). (b) illustrates its placement relative to the operating room table, such that sterile field conditions are maintained. Energy delivered to the specimen to create a fracture is controlled by the release height of the pendulum mass. (c) schematically illustrates a purpose-designed tripod pin fixation system for creating distal tibial articular surface fractures. A subarticular surface stress-rising saw cut is employed to ensure reproducibility of fracture morphology. Energy that passes through the specimen is determined by displacement of the sled.

pendulum mass will be absorbed by the joint during the fracture event [19]. While the pendulum itself would not “swing through” the specimen, as happens in an Izod or Charpy test, nevertheless, a substantial portion of the delivered energy will pass through the specimen and will be absorbed elsewhere, in series, by the overall testing setup. If this through-passed energy could be measured, the difference between the delivered energy and the through-passed energy would correspond to the energy absorbed in the specimen. In the pendulum system, the magnitude of energy delivery ($KE = \frac{1}{2}mv^2$) is calculated from the pendulum mass (6.1 kg) and its linear velocity, v , at impact, where linear velocity is derived from the product of angular velocity (measured by a potentiometer at the pendulum pivot) times the length of the pendulum arm. Use of the kinetic energy as the delivered energy, rather than its nominally equivalent potential energy ($PE = mgh$), corrects for friction losses at the pendulum arm pivot bearing. The mass of the pendulum arm (0.80 kg), distributed uniformly along its 1.0-m length, is neglected; thus, the actual delivered kinetic energy may be slightly greater than the value calculated using the pendulum mass only.

For setup of the system prior to a test, the specimen tripod support is positioned on the sled such that, at impact, the pendulum will be exactly vertical (i.e., KE is maximum), the sled stationary, and the spring uncompressed. The pendulum mass is then raised to a predetermined height and released. The mass impacts the tripod anchor, driving the talus into and fracturing the tibia [17]. During the fracture event, the spring acts to decelerate the sled from its immediate postimpact velocity until bringing it to a stop. A linear potentiometer mounted in parallel with the sled measures the sled’s maximum displacement, x , at the instant of stopping. The through-passed energy (i.e., the energy transferred from the specimen to the sled) is calculated by $TE = \frac{1}{2}kx^2$, where k is the spring constant. Raw analog voltage signals from the angular (pendulum) and linear (sled) potentiometers are digitized at 15 kHz using LABVIEW and converted into energy data using a custom MATLAB script. The difference between (preimpact) kinetic energy of the pendulum mass and the through-passed energy transferred to the sled is thus, the specimen’s absorbed energy (AE), $AE = KE - TE$.

To validate the energy absorption measurements, a polymer foam surrogate for what would otherwise be a minipig hock joint was utilized. A necessary characteristic of this surrogate material was that its energy absorption properties be uniform and measurable. Based on previous empirical experience [16], rigid polyurethane foam (25 lb/ft³ density, Last-a-Foam, General Plastics Mfg. Co., Tacoma, WA) was chosen. Eighteen identically sized blocks (5.5 × 5.5 × 4.0 cm) of the foam were cut and impact-tested with the pendulum system. Rather than employ the tripod-mounting fixture used to test animal joints, each foam block rested on the smooth surface of the sled in contact with a rigid, flat-ended cylindrical indenter (11.7 mm diameter), that was in turn rigidly affixed to the sled (Fig. 2). Trial-and-error with different-sized indenters was used to find the largest diameter that would create an easily detected and measured indentation (depth > 0.50 mm) at the lowest impact energy. As with the hock joint fracture tests, the pendulum mass was raised and released for this test configuration, driving the block into the indenter. The digitized linear and rotary potentiometer signals were used to determine the impact duration, that was measured from the initial contact (pendulum vertical) until the time when the pendulum and sled-mounted indenter moved in unison (i.e., when no further penetration of the indenter occurred). For the impacts, durations ranged from approximately 20 ms to 40 ms. Six blocks were tested at each of three different pendulum drop heights (input KE), corresponding to 20 deg, 40 deg, and 60 deg pendulum release angles, and the absorbed energy (AE) was calculated for each test. The depth of indenter penetration for each impact was subsequently measured using a digital caliper (± 0.01 mm).

To provide a “gold standard” independent measurement of energy absorption of the foam, the same indenter (removed from the pendulum system sled) was mounted to an MTS servohydraulic test machine’s actuator. Each of the 18 previously pendulum-impacted blocks was supported on the MTS load cell, and the indenter was driven into the block at a site adjacent to that of the pendulum impact. The actuator was displacement-control programmed to nominally apply similar penetration depths as

Fig. 2 The pendulum system configured to measure energy absorbed in indentation of a rigid polyurethane foam block. At impact, the pendulum drives the block into the indenter, which is rigidly mounted on the low-friction sled. As the block is driven into the indenter, the sled moves to the right, resisted by an initially uncompressed spring. The energy absorbed by the block equals the difference between the kinetic energy of the mass and the energy through-passed to the spring. The spring constant (36.7 N/mm) had been determined by empirical measurement.

those obtained with the pendulum. The full penetration depth was reached via a 50-ms linear ramp in all tests, the maximum rate obtainable while maintaining closed-loop stability. Although this was slightly longer than the pendulum impact durations, experimentation at other rates showed no evidence of significant rate dependency. All indentation depths were directly caliper-measured, and absorbed energies were determined via integration of the MTS load-displacement curves.

Following the system validation tests, a preliminary series of cadaveric hock specimen experiments was conducted to determine appropriate parameters (e.g., pendulum mass, drop height, and length and stiffness of the compression spring) required to achieve bone fracture. Four representative tibial plateau fractures from the

cadaver series are shown in Fig. 3. They exhibit the general clinical appearance of human fractures—the primary fracture lines are medial-lateral and an intact anterior fragment of less than one-half of the total articular surface area is minimally displaced. After the parameters were established, the pendulum impaction system was used in an institutionally approved (IACCUC #1007141) survival animal study, in which experimental IAFs were created in 14 minipig hocks in vivo (approximate age 2 years and weight 90 kg).

Results

Results of the foam surrogate tests for 18 blocks are summarized in Table 1. They were pendulum-impacted, six blocks at each of three release heights, absorbed energies were calculated, and the penetration depths were caliper-measured after each test. The blocks were then MTS-impacted under displacement control, with the target penetration depth for each group set to the average depth obtained in the pendulum impacts—the actual penetration depths reached were directly caliper measured. Absorbed impact energies for both impact types were plotted versus penetration depths, and linear regressions showed strong correlations (Fig. 4). Pendulum impact-absorbed energy versus MTS impact-absorbed energy is plotted in Fig. 5.

Pendulum system energy results for the 14 individual live-animal hock joint fractures are reported in Table 2. Energy delivered (KE) ranged from 31.5 to 48.3 Js (41.3 ± 4.0 , mean $\pm$ s.d.). The low delivered energy for animal number one (31.5 J) was due

Fig. 3 Pendulum-created porcine cadaver distal tibia fractures produced during experiments to establish the appropriate system parameters for subsequent use in live-animal tests. The fractures exhibit the general clinical appearance of human fractures: the fracture lines are predominately medial-lateral and an anterior fragment is minimally displaced. (A = anterior, P = posterior, L = lateral, M = medial).

Table 1 Pendulum-determined versus MTS-determined absorbed energies for impacts of 18 identical polyurethane foam blocks

Pendulum-applied impacts Three drop heights ($n = 6$)		MTS-applied impacts Three target penetration depths ($n = 6$)	
Absorbed energy avg. (s.d.) (J)	Penetration depth avg. (s.d.) (mm)	Absorbed energy avg. (s.d.) (J)	Penetration depth avg. (s.d.) (mm)
0.80 (0.09)	0.67 (0.11)	0.82 (0.08)	0.74 (0.08)
3.82 (0.11)	3.29 (0.14)	4.01 (0.11)	3.52 (0.11)
9.21 (0.33)	6.92 (0.17)	7.63 (0.16)	6.55 (0.12)

Fig. 4 Absorbed energy (J) versus penetration depth (mm) for pendulum and MTS impacts of 18 identical foam surrogate blocks

Fig. 5 Pendulum-impact absorbed energy (J) versus MTS-impact absorbed energy for 18 foam surrogate blocks

Table 2 Survival-animal hock joint fracture energy test results for 14 minipigs. AE/KE is the proportion of absorbed energy to pendulum-delivered kinetic energy.

Animal #	Kinetic energy KE (J)	Through-passed energy TE (J)	Absorbed energy AE = KE - TE (J)	AE/KE (%)
1	31.5	14.7	16.9	53.5
2	43.7	15.4	28.3	64.7
3	41.2	19.8	21.4	51.9
4	38.1	18.4	19.7	51.6
5	41.1	19.9	21.2	51.6
6	38.3	18.3	20.0	52.2
7	41.7	19.1	22.6	54.2
8	41.0	20.6	20.5	49.9
9	39.1	21.8	17.3	44.2
10	40.9	18.9	22.0	53.9
11	43.6	19.5	24.1	55.2
12	44.9	20.5	24.4	54.4
13	48.3	20.0	28.2	58.4
14	44.4	19.8	24.6	55.3
Average (s.d.)	41.3 (4.0)	19.0 (1.9)	22.2 (3.5)	53.6 (4.5)

to a lower pendulum drop height used for that specimen only. Through-passed energy (TE) ranged from 14.7 to 21.8 Js (19.0 ± 1.9), and absorbed energy (AE) ranged from 16.9 to 28.3 Js (22.2 ± 3.5). The proportion of absorbed energy to energy

Fig. 6 Absorbed energy (J) versus delivered kinetic energy (J) for 14 survival-animal hock joint fractures produced by the pendulum device

delivered ranged from 44.2% to 64.7% ($53.6\% \pm 4.5\%$). Absorbed energy versus delivered energy is plotted in Fig. 6.

Discussion

The instrumented pendulum impactation system documented in the present study measures the magnitude of energy absorption during experimental impactation in terms of the difference between the delivered and through-passed energy magnitudes. To our best knowledge, this system is the first to enable energy absorption measurement in biomechanical impactation settings.

For the foam surrogate validation study, pendulum-absorbed energies were slightly greater than MTS-absorbed energies for similar penetration depths, particularly at the highest delivered energy (Table 1 and Fig. 5). This was not unexpected, as the pendulum device accounts for energy absorbed by the entire system, including penetration, friction, and deflection or vibration of the (nonspring) components of the pendulum device itself, whereas the MTS test isolates the energy expended only in penetration. The nonpenetration absorbed energy effects in the pendulum device may become larger with higher delivered energies. However, the generally good agreement between the pendulum-determined absorption energy and the MTS-determined absorption energy suggests that such energy losses are minor.

As is apparent from the results of the survival-animal pendulum-induced fractures (Table 2), only a portion (53.6%) of the delivered energy was absorbed in creating the experimental injury, while a significant amount (46.4%) passed through the hock specimen, subsequently being absorbed in spring compression. The relationship between absorbed and applied energy is linear (Fig. 6). However, caution is urged in applying this relationship to other fracture studies. In the present fracture impactation setting, there can be a variety of factors that contribute to energy absorption during an impactation event, including nonbone-fracture factors, such as soft tissue damage/deformation. The current technique does not permit discriminating the energy absorption directly associated with bony fracture versus these nonfracture factors. (Imaging techniques for estimating bone-fracture energy from computed tomography-based assessment of de novo interfragmentary-free surface area have recently been developed [20] but are outside the scope of the present study.) However, the present survival experiment results indicate that, at least in this range of impactation parameters for this particular surgical preparation, delivered energy is clearly not a sufficient measure of the energy actually absorbed in creating tissue injury.

Presumably, the degree of discrepancy between delivered versus absorbed energy in any given impactation experiment would be specific to considerations such as specimen type, support fixation arrangement, impactation parameters, etc. Nevertheless, the

substantial disparity (46.4%) apparent in this particular experimental setting, seemingly at least generally representative of many laboratory biomechanical impaction experiments, serves to vividly illustrate the fallacy of presuming that delivered energy is necessarily representative of the energy actually involved in causing specimen tissue damage. The sled-spring arrangement used in this particular experimental setting arose as an outgrowth of an already-in-use impaction system. Obviously, however, a wide variety of similarly conceived instrumentation designs might well be used to implement the same underlying concept in other specific study designs.

While it might be possible to design/perform experiments where absorbed energy much more closely approximates delivered energy (based on empirical trials), biologic variability is such that many such trials might fail to produce bony fracture, thus, requiring (biologically confounding) repeat impactions. So, for practical purposes, it is desirable to deliver kinetic energy levels that are amply large to reliably achieve fracture, which in turn presumes that through-passed energy levels will, in general, be nonnegligible.

Acknowledgment

This research was supported by NIH CORT grant P50 AR055533 and DOD grants W81XWH-10-1-0864 and W81XWH-11-1-0583.

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