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Single and incremental trauma models: a biomechanical assessment of spinal instability

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Abstract Biomechanical analysis of spinal injury in the laboratory requires the development of trauma models that simulate spinal instability. Current experimental trauma protocols consist of two types: single or incremental impacts. The incremental protocol has several advantages. However, the equivalence of the spinal instabilities produced by the two trauma protocols is currently unproven. The purpose of this study was to investigate whether the single and incremental trauma models produce equivalent soft tissue instabilities in the lumbar spine. Ten freshly frozen porcine lumbar spines were divided into two functional spinal units (FSUs), L2-L3 and L4-L5. FSUs were then randomized to either the single trauma (ST) or incremental trauma (IT) protocol. The IT protocol consisted of four sequentially increasing high-speed axial compression traumas, while the ST protocol was a single impact of the same magnitude as the final trauma of the IT. Before and after the final trauma, each FSU underwent flexibility testing under flexion/extension, lateral

bending, and axial torsion pure moments. No significant differences were found in neutral zone or range of motion between IT and ST specimens in any of the three axes of motion, either before or after the trauma. In addition, no differences were found between the normalized motions of the IT and ST groups. The FSUs subjected to incremental trauma do not suffer greater injury than those subjected to a single impact. The data support the equivalency of the subfailure soft tissue injuries of the spine caused by the incremental and single trauma protocols respectively. This finding is important, because only with the incremental trauma protocol is one able to obtain injury threshold, study injury progression in the same specimen, produce a defined injury more accurately, and efficiently utilize scarce human cadaveric specimens.

Keywords Instability · Biomechanics · Lumbar spine · Incremental trauma · Subfailure injury

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Introduction

Traumatic injuries to the thoracolumbar spine are serious and disabling injuries, which present a major problem to society both economically and personally. They are among the most common causes of severe disability and death following trauma and their diagnosis is frequently delayed [1].

As the spine functions to transmit load, allow motion, and protect the vital spinal cord and nerve roots; it also allows for both physiologic and pathologic motions depending on the integrity of the osseous and ligamentous structures. Injuries to the spine can include fractures and/or soft tissue injury. Fractures or osseous injury can be documented with various diagnostic modalities including plain radiographs and computerized tomography; on the other hand, soft tissue injury is more difficult to diagnose directly.

Increased intervertebral motion is a sign of soft tissue injury and has been incorporated into the clinical definition of instability. Clinical instability is defined as the loss of the ability of the spine, under physiologic loads, to maintain relationships between vertebrae in such a way that there is neither damage nor subsequent irritation to the spinal cord or nerve roots and, in addition, there is no development of incapacitating pain or structural deformity [13].

To further study the biomechanical basis of clinical instability, we need to develop biomechanical models that mimic the trauma experienced by the soft tissues clinically. Biomechanical information is most commonly obtained through experimental testing with cadaveric specimens. Two kinds of experimental *in vitro* models have been developed to reproduce these injuries; the single and the incremental trauma protocols. In the single trauma model, a spinal segment with intact ligamentous structures is subjected to a single traumatic event. In the incremental trauma model, the specimen is subjected to a series of traumas of increasing energy until the injury of a specific magnitude is produced.

The incremental trauma model has many advantages over that of the single trauma model, as described previously by Panjabi and Hoffman [9]. They include the following:

- It is possible to observe and investigate the progression of injury from mild to severe, by studying the same specimen after each incremental trauma event.
- It facilitates the determination of an injury threshold.
- A given clinical injury is more accurately produced experimentally.
- Overall, the incremental protocol minimizes the number of specimens required.

The latter is important due to the increasing costs of human cadaveric specimens and specimen variability due to differences in age, sex, bone density, and degenerative changes. In comparison, the single trauma protocol results in only one level of injury severity, which may or may not be the one desired. A concern with the incremental trauma approach, however, is the possibility that the results of the final trauma may be biased by the prior sequential traumas. In other words, the final results of the two protocols may be different. Recently, the two protocols were investigated in a bone-ligament-bone model [10]. The findings showed that the two protocols were statistically equivalent.

To our knowledge no study has investigated whether the two approaches produce biomechanically equivalent soft tissue instabilities in a complex unit such as the spine. This information is necessary in order to justify the use of the incremental model in future laboratory experiments. We hypothesized that the biomechanical characteristics of two groups of functional spinal units (FSUs) traumatized to result in soft tissue injury by the incremental and single trauma protocols respectively, would be equivalent.

Materials and methods

Specimen preparation

Ten freshly frozen porcine lumbar spines were obtained. The original animals were all less than 1 year of age and weighed approximately 50 kg. The specimens (L2-L5) were dissected of the muscle, sparing all ligamentous structures including facet capsules and discs. Each specimen was divided into two FSUs (L2-L3 and L4-L5). A functional spinal unit is a two-vertebrae spinal segment with all the interconnecting ligaments and disc intact. A total of 20 FSUs were used. FSUs were randomly assigned to the incremental trauma or single trauma protocol such that five L2-L3 FSUs and five L4-L5 FSUs were present in each group.

The FSU was prepared by applying a polyester-based resin to the caudad and cephalad vertebrae. The disc space was aligned horizontally in both the sagittal and coronal planes, and the specimen alignment was confirmed with plain radiographs. The specimens were wrapped in normal saline-soaked gauze and stored in sealed plastic bags at -20°C until tested.

Flexibility testing

The multidirectional mechanical properties of the specimen when intact and after trauma were quantified by the flexibility test. The flexibility test requires the application of a load and the measurement of the resulting intervertebral motion [7, 8]. A specially designed apparatus was utilized so that the loads (pure moments) applied to the spine remained unchanged and the specimen was allowed unconstrained motion, while it underwent complex movement. In this apparatus the caudal end of the specimen was fixed to the test table, while loads were applied to the free cephalad end. The loads consisted of three pairs of pure moments: flexion/extension, right/left axial torque, and right/left lateral bending.

Fig. 1 Diagrammatic representation of a specimen and the high-speed trauma apparatus

Moments were applied individually in three equal steps to a maximum value of 3.0 Nm. This load magnitude had been found, in preliminary studies, to not cause damage to the specimen (even after the final trauma). The moments were applied in three load-unload cycles to precondition the specimen. After each load-step in each load cycle, and on unloading, the specimen was allowed to creep for 30 s to reduce the viscoelastic effects of the spine. In the third load cycle, three-dimensional intervertebral rotations were measured at each load step, using a non-contacting optoelectronic motion measurement system (Optotrak, Northern Digital, Waterloo, Canada).

Trauma production apparatus

The method used for high-speed experimental spinal trauma has been well-documented [6]. A brief description follows. The lower mount of the specimen was fixed on top of a multidirectional load cell (AMTI, Boston Model MC6–6–4000). The specimen was traumatized by dropping a mass through a Plexiglas guide tube onto an impounder resting on top of the upper mount of the specimen. Motion of the impounder was guided by linear bearings aligned vertically. Thus, the unconstrained specimen was loaded in axial compression (Fig. 1).

Trauma experimental protocols

The experimental protocols can be visualized with the timeline provided in Fig. 2. Prior to trauma, specimens in both the incremental trauma and single trauma groups underwent flexibility testing. This initial flexibility testing provided data for the intact state of each specimen. After the flexibility testing, the incremental trauma specimens underwent consecutive incremental traumas of 1, 2, 3, and 4 kg dropped from a 1.4-m height. In other words, the kinetic energy applied to the specimens was 13.7 Nm the first time, and then it increased by 13.7 Nm, to the maximum of 54.8 Nm.

After each traumatic impact, the specimen was given 1 h of rest to allow for viscoelastic recovery of the ligamentous structures. In order to control for the total rest time between the two groups, the FSUs randomized to single trauma were also rested for 3 h prior to their single 4-kg impact. After the final impacts, all FSUs were radiographed in orthogonal planes to ensure that no fractures had been caused by the traumas. Each specimen then underwent flexibility testing for a second time to provide data for the injured state. During the entire experiment, the specimen was wrapped in normal saline-soaked gauze to keep it well hydrated.

Fig. 2 The experiment design, showing the sequence of events of the two protocols

Data analysis

Raw data from the flexibility tests were analyzed to determine neutral zone and range of motion parameters in three planes of motion: flexion/extension, axial rotation, and lateral bending [11]. The positive and negative rotations in each plane were summed. For example, in the lateral bending plane, the left and right lateral bending rotations were added together to obtain the total lateral rotation.

In order to quantify the increased flexibility due to the final trauma, each value was individually normalized with respect to the corresponding intact value. This parameter was called “injury potential”. The injury potential equaled rotation after injury divided by rotation when intact [12]. For instance, the intact specimen will have an injury potential of 1. A higher value represents potential instability.

To document the presence of injury due to the trauma for both trauma groups, the intact (no trauma) and injured (4 kg of trauma, either single or incremental), flexibilities were compared within each group. To assess whether differences existed between the incremental and single traumas, the incremental trauma flexibility data were directly compared with the single trauma data in both the intact and injured states. The above comparisons were performed using a two-factor analysis of variance and post hoc *t*-tests, with a significant *P*-value set at 0.05. Lastly, the injury potential data of the two groups were compared with paired *t*-tests.

Results

The analysis of variance of the raw data focused on two factors: presence of injury – (intact vs injured) and type of trauma (incremental vs single). However, no differences were found between the incremental and the single trauma type groups.

Presence of injury

Post hoc comparisons of the neutral zone data between the intact and injured states demonstrated significant differ-

Table 1 Neutral zone (in degrees). Average ($\pm$ standard deviation) values before and after final injury. Included are the resultant post hoc *t*-test *P*-values, with significant differences ($P < 0.05$) noted by asterisks (*)

	Intact	Injured	Intact vs injured
Flexion/extension			
Incremental trauma	5.11 $\pm$ 1.63	9.01 $\pm$ 3.12	$P=0.004^*$
Single trauma	6.91 $\pm$ 4.23	10.90 $\pm$ 5.09	$P<0.001^*$
Incremental vs single	$P=0.251$	$P=0.195$	
Axial rotation			
Incremental trauma	1.11 $\pm$ 0.89	1.29 $\pm$ 1.22	$P=0.673$
Single trauma	0.81 $\pm$ 0.41	1.31 $\pm$ 0.96	$P=0.172$
Incremental vs single	$P=0.145$	$P=0.827$	
Lateral bending			
Incremental trauma	9.15 $\pm$ 2.21	11.65 $\pm$ 3.36	$P=0.032^*$
Single trauma	9.09 $\pm$ 1.38	10.91 $\pm$ 1.84	$P=0.018^*$
Incremental vs single	$P=0.917$	$P=0.52$	

Table 2 Range of motion (in degrees). Average ($\pm$ standard deviation) values before and after final injury. Included are the resultant post hoc *t*-test *P*-values, with significant differences ($P < 0.05$) noted by asterisks (*)

	Intact	Injured	Intact vs Injured
Flexion/extension			
Incremental trauma	9.58 $\pm$ 2.32	15.12 $\pm$ 4.47	$P < 0.001^*$
Single trauma	12.56 $\pm$ 6.38	17.90 $\pm$ 7.22	$P = 0.001^*$
Incremental vs single	$P = 0.169$	$P = 0.146$	
Axial rotation			
Incremental trauma	2.45 $\pm$ 1.09	3.63 $\pm$ 1.66	$P = 0.015^*$
Single trauma	2.75 $\pm$ 1.24	3.99 $\pm$ 1.35	$P = 0.014^*$
Incremental vs single	$P = 0.627$	$P = 0.546$	
Lateral bending			
Incremental trauma	12.49 $\pm$ 2.35	15.99 $\pm$ 4.48	$P = 0.017^*$
Single trauma	12.73 $\pm$ 2.06	14.84 $\pm$ 1.80	$P = 0.008^*$
Incremental vs single	$P = 0.610$	$P = 0.446$	

Table 3 Injury potentials. Comparison of average ($\pm$ standard deviation) values between incremental and single trauma groups. Both neutral zones and ranges of motion are shown. Injury potential is the ratio: injured motion divided by intact motion. No significant differences ($P < 0.05$) were found

	Neutral zone	Range of motion
Flexion/extension		
Incremental	1.97 $\pm$ 0.70	1.69 $\pm$ 0.40
Single	1.71 $\pm$ 0.42	1.56 $\pm$ 0.39
Incremental vs single	$P = 0.254$	$P = 0.381$
Axial rotation		
Incremental	1.56 $\pm$ 1.16	1.46 $\pm$ 0.64
Single	2.58 $\pm$ 2.75	1.94 $\pm$ 1.76
Incremental vs single	$P = 0.312$	$P = 0.464$
Lateral bending		
Incremental	1.30 $\pm$ 0.39	1.30 $\pm$ 0.39
Single	1.22 $\pm$ 0.30	1.15 $\pm$ 0.23
Incremental vs single	$P = 0.655$	$P = 0.417$

ences in flexion/extension and lateral bending for both types of trauma (Table 1). Range of motion data comparisons revealed significant differences in flexion/extension, axial rotation, and lateral bending for both incremental and single trauma types (Table 2).

Type of trauma

Individual post hoc comparisons were also performed between the incremental and single trauma types in both the intact and injured states. For both neutral zone and range of motion data sets, no significant differences were found (Table 1, Table 2).

Fig. 3 Injury potential, normalized, of neutral zone (A) and range of motion (B). No significant differences ($P < 0.05$) were found between the incremental and single trauma groups. Intact specimens have an injury potential of 1.0, represented by a horizontal line

The injury potential data and the results of the paired *t*-tests are presented in Table 3. No differences were found in the normalized neutral zone or normalized range of motion data between the incremental and single trauma groups. To illustrate the results in all three planes of motion, the average normalized neutral zone and range of motion data, i.e. injury potentials, are presented in Fig. 3A,B.

Discussion

The present study was designed to answer one biomechanical question: Are the single and incremental approaches to trauma modeling equivalent when producing soft tissue instability in a complex structure such as the spine? In answering this question, our study validated the presence of subfailure ligamentous injury using flexibility testing. This study also directly compared the post-traumatic instabili-

ties due to the incremental and single traumas. Lastly, the injury potential of the two groups were analyzed.

We found that the ranges of motion of the injured state (in all three planes) were significantly greater than those of the intact state. The significant increases in range of motion and in neutral zone demonstrated the presence of injury within both the incremental and single trauma groups. Additionally, we found that the FSUs subjected to incremental trauma do not suffer greater injury than those subjected to the single impact. There was no statistically significant difference between these two groups in any motion direction, either before or after the final trauma. The lack of significant difference was demonstrated in both the neutral zone, which has been found to be a sensitive parameter to measure changes in spinal stability [5, 7], and the range of motion.

In order to better ascertain the effects of the injury on each specimen, a ratio called the injury potential was obtained. This ratio provides information on the relative change an individual specimen underwent secondary to the injury it suffered. Using the injury potential, any bias due to specimen variability could be minimized. Consequently, injury potential is a sensitive parameter when comparing the results of two different injury techniques. In analyzing this injury parameter, again no significant differences were found between the incremental and single trauma groups, either in the neutral zone or in the ranges of motion.

Both single and incremental trauma biomechanical protocols have been used to study spinal trauma. The positive aspects of the single impact approach include a one-time specifically produced injury and the theoretical avoidance of specimen fatigue. For example, Fredrickson and Mann used a single-impact loading technique with impact energies of 260 Nm [2]. They contend that their approach was a reproducible technique for creating burst fractures *in vitro*, despite a wide range of fracture severity, with canal compromise ranging from 4 to 46%. Panjabi and Hoffman also found that using a single trauma technique produced a large variation in burst fracture severity [9]. The Fredrickson study suggested that the selection of suitable specimens is a critical step for reproducibly simulating burst fractures with a single trauma.

There have been a number of previous studies that have employed the incremental approach to model musculoskeletal trauma [7, 9, 11]. For example, Oxland and Panjabi studied soft tissue injury to the porcine cervical spine using the incremental trauma approach [7]. In their study, successive high-speed compression impacts produced increased instability, measured as statistically significant changes in the flexibility parameters of neutral zone and range of motion, permitting the evaluation of soft tissue injury progression. Panjabi and Hoffman used human lumbar spine specimens and a similar incremental approach to study burst fractures [9]. In addition to studying the injury progression, they were able to determine the

injury threshold for human thoracolumbar specimens – a significant advantage of the incremental approach. Therefore, they were able to produce a burst fracture with the desired canal encroachment. Grauer and Panjabi also used an incremental trauma approach for whiplash simulation to determine threshold accelerations that resulted in significant changes in injury potential [3].

None of these spinal trauma studies, however, were designed to investigate the equivalency of the single and incremental trauma protocols. The validity of the incremental trauma results relies heavily upon the fact that an incremental trauma protocol produces instabilities that are similar to those of a single trauma protocol. The equivalence between these two protocols has been recently demonstrated, but in a less complex bone-ligament-bone model [10]. In that study, the isolated ligaments that were incrementally traumatized in four steps to the final trauma of 80% of the failure deformation, demonstrated the same biomechanical behavior as the ligaments that suffered a single trauma of 80% of the failure deformation. The current study is the first to evaluate the differences between the incremental and single trauma models in a complex structure – a functional spinal unit – which includes osseous, cartilaginous, and ligamentous structures as well as the intervertebral disc.

This is an *in vitro* model with associated limitations, due to lack of muscles, healing and adaptation. The flexibility protocol, to evaluate injury/instability, was designed to apply non-constraining non-injurious physiologic pure moments to the specimen. We applied a maximum moment of 3.0 Nm, which was shown by preliminary studies to not further injure the specimen. Whether this moment magnitude produced physiological motions is not known, as there are no data concerning porcine physiological motions. We did not use preload in our model, to keep the experiment simple. However, the purpose of our study was to evaluate the two protocols on a relative basis using exactly the same model. To this end, we believe, our conclusions are unaffected due to the lack of the preload. We used porcine spines for their uniformity concerning weight, age, gender and degeneration. As the vertebral anatomy and soft tissue mechanical properties are not dissimilar from those of human spines, we believe the choice of the porcine specimens is appropriate.

The advantages of the incremental trauma protocol are many compared to those of the single trauma protocol. The incremental protocol offers the ability to:

- Study injury progression with the specimen serving as its own control, from mild to severe
- Determine specimen-specific injury thresholds
- Produce a defined injury, and
- Efficiently utilize precious human cadaveric specimens

There are some theoretical drawbacks to the incremental trauma approach. One may feel that this type of protocol produces an additive injury at each increment, which will

affect the eventual outcome of the specimen. We did not find this to be true. The incremental group specimens, after a four-step trauma protocol, displayed no evidence of additive injury or fatigue failure. Cyclic loading, which may involve hundreds or thousands of load cycles, on the other hand, has been shown to cause endplate fatigue failure in the spine [4].

Conclusions

The incremental trauma protocol produced spinal injury, defined by the three-dimensional flexibility test, that was

equivalent to the injury sustained in the single trauma protocol. This is a critical issue in the field of in vitro biomechanical research, where specimens, especially human, are expensive, variable in their sex, age, and bone quality, and not repairable. Directly comparing the effects of single and incremental trauma protocols using a complex anatomic system such as the functional spinal unit, our results demonstrated no significant differences between these two protocols. Thus, the incremental trauma protocol, which has many advantages, is the protocol of choice for experimental trauma studies of the spine.

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