IMPACT EXPERIMENTS IN ORTHOPEDIC BIOMECHANICS

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INTRODUCTION: A better understanding of the fracture mechanism, kinematics of the anatomic structure and tissue tolerances can improve clinical prognosis and the design of anthropomorphic test devices. In this study an impact apparatus was designed to do experiments in-vitro on three areas of orthopedic biomechanics, on either hard or soft tissue. This study included three topics: cervical vertebra fractures, Achilles tendon injuries and calcaneal fractures under impact loading.

For practical reasons immature bovine and mature porcine specimens, especially the latter, have been the most popular ones used as the model for in-vitro or in-vivo mechanical studies [1,2]. Most studies have classified spinal fractures and dislocations based on radiographic information in order to understand the fracture patterns and instabilities produced by cervical spinal fractures [3,4]. We have attempted to produce clinically-relevant fractures under high speed impact using porcine cervical vertebrae to analyze the mechanical responses of bones and discs in both fractured and non-fractured specimens.

Musculotendinous strain injuries have been cited in clinical medicine as among the most common injuries. In recent years many studies have been done examining muscle strain injuries [5,6,7]. Usually they used MTS with slower deformation rates from quasi-static to 50 cm/sec, in contrast to real life injuries, which are usually sudden and fast. Therefore the purpose of this study was to cause high speed Achilles tendon strain injuries and to examine the biomechanical, functional, and structural changes associated with muscle-tendon trauma.

A number of different techniques have been described for internal fixation of calcaneal fractures [8,9,10]. Although the stability of the fixation is an important factor in maintaining the position of the reduction, it is not known what fixation strength is necessary to achieve bone union with satisfactory alignment and the biomechanical behavior of these techniques. However, little has been reported for intra-articular fractures of the calcaneus. In this study, we compared the fixation strength of two types of fixation methods, namely lateral buttress plating with or without a longitudinal transfixing screw. Based on this information, a better method of internal fixation for calcaneal fractures could be selected for clinical use.

METHODS: The specimens were subjected to high-speed trauma produced by an impact apparatus. This testing setup is a falling weight system which can produce axial and eccentric impacts for different objectives of orthopedic studies. A special design was employed to assure there would be only one impact on the specimen used for biomechanical analysis. A high-speed camera was placed in front of the specimen to record the trauma even at the speed of 2500 frames/sec. In this study, the specimens included porcine vertebrae, rabbit Achilles tendons, and human cadaver legs. X-ray and/or CT scans provided observational details.

A total of ten fresh cervical porcine spines were used. Three cervical vertebrae segments (C3-C5) were prepared. The upper (C3) and lower(C5) vertebrae were embedded in a circular plastic model with polyester-based resin (4 cm in depth and 12 cm in diameter) so that the middle vertebrae (C4) were vertically aligned. After mounting the specimen, radiographs and computerized tomograms (CT) were taken to examine the specimen and to determine the quantitative computerized tomogram (QCT) values of the middle vertebrae (C4). Before impact, several steel balls (1/16" in diameter) were glued onto the vertebral surface near the upper and lower discs to make it possible to observe the deformation of the vertebral body and disc during impact. All the specimens were subjected to high-speed trauma produced with a guided drop mass. This was raised to a height of 1.75 m in the guided tube, and was estimated to have an impact velocity of 5.86m/sec under frictionless conditions. To stimulate the flexion-compression trauma, eccentric impact was achieved by shifting the cylinder 2 cm anterior to the geometric center. The force-time curves were obtained from sequential data. For deformation of the intervertebral disc during impact, the deformation-time curves were obtained by the digitalization of the high speed film. After impact, the specimens were then divided into two groups, fractured or non-fractured, for further analysis. QCT values between the fractured and non-fractured groups were also compared.

For the experimental analysis of Achilles tendon injuries, sixteen specimens were used in this study. The drop weight was gradually increased and dropped from a fixed height of 50 cm until failure occurred. The traction processes were recorded by high speed camera.

Thirty-six fresh frozen specimens of human legs were impacted by a 20 kg weight dropping from a height of 155 cm to create calcaneal fractures. Among them, twelve specimens, which had both longitudinal and transverse primary fractures, were selected for simulated open reduction and internal fixation and divided into two groups. In group 1, a lateral buttress plate and parallel screws in the latero-medial direction were used. In group 2, a longitudinal screw transfixing the transverse primary fracture line was added. Afterwards, biomechanical testing with a vertical shank load was applied until the internal fixation failed.

RESULTS: Spinal fractures were successfully produced in porcine spines by impact testing. The deformations of the discs and the kinematical stability of the spinal experimental segments were also found. In total, six specimens fractured. Usually the fractures occurred on the lower vertebrae, that is, C4 or C5. These fractures were very similar to those occurring clinically in human spines. In burst fractures, the spinal canal was narrowed by retropulsed bony fragments. In the maximal force-time curve of the fractured group, there was a steep decline immediately after the climax, then the curve rose again, i.e., there were two characteristic peaks in the curve. However, in the non-fractured group there was only one peak in the curve. The duration of trauma events in the fractured group averaged about 27 ms, which was much longer than that for the non-fractured group (18 ms).

For the experiment on the Achilles tendon, The high speed traction mechanism produced strain injuries to the specimens and obtained the immediate tensile force in the traction process. The results showed nine specimens ruptured in the femur,

six in the muscle, one in the Achilles tendon. These experimental data suggest: 1) the structure of the Achilles tendon is too complicated to identify each peak of the data acquired, and 2) Achilles tendon rupture is rare in this in-vitro pilot study.
Clinically-relevant fractures under high speed impact were produced on internal fixation for calcaneal fractures. The specimens with both longitudinal and transverse primary fracture lines were selected for simulated open reduction and internal fixation. All mechanical failures of the reconstructed calcaneus occurred on the transverse primary fracture line. The average failure load was 805$\pm$356 N in group 1 and 2095$\pm$910 N in group 2 (Wilconon $p<0.05$). In group 1, the anterior and posterior parts of the calcaneus were driven apart. The anterior or middle facets were disrupted and the buttress plate at the lateral calcaneus distorted. However, the screws in the thalamic portion fixing the longitudinal primary fracture line remained intact. After adding a longitudinal transfixing screw in group 2, the failure still occurred on the transverse primary fracture line, and the longitudinal screw was usually bent when the specimen was loaded to the point of failure. The internal fixation had a 3.5 times greater force to failure ratio compared to that of group 1. Wilconon rank statistical analysis revealed that this difference is significant.

CONCLUSIONS: Impact experiments are useful for basic research in orthopedic biomechanics. The results from animal models provide useful insights into human bone fractures. The repeatability and reproducibility of animal tests offer a great opportunity to evaluate spinal fracture mechanics. Five specimens fractured either in the C4 body inferior or the C5 body superior, and only one fracture occurred in the C3 body. The bone strength of the C3 body was supposed to be the weakest, but most of the fractures occurred in the C4 or C5. Panjabi noted that for compression trauma, the force-time curves for all specimens displayed significant variability, with the presence of large bending moments in the sagittal plane. Therefore we conclude that external force and structural support are the major factors which produce fractures in C4 and C5 bodies. The pattern of a single steep downward decline in the curve was always found in the fractured group. These were important characteristics for judging whether a specimen was fractured or not during impact experiments. On the deformation-time curve, the C4-C5 disc in the fractured group always had a much larger deformation than in the non-fractured group. On the other hand, the C3-C4 discs did not display many differences between the fractured and non-fractured groups. They recovered immediately after a short, small deformation.
The test with the Achilles tendon injury was only a pilot study, and a well-designed protocol is needed to improve the results.
The forces producing fractures of the calcaneus are combined compression and shear under a cranio-caudal impact. Moreover, the main patterns in the biomechanics of calcaneal fractures are the time of stroke and geometric position of the foot at the moment of impact [11]. As the specimens were maintained in a neutral position, the compression of the talo-calcaneal joint led to an impact of this structure, thereby producing the joint depression type together with sagittal shear fractures. Accordingly, simulated calcaneal fractures with both longitudinal and transverse primary fracture lines would be the main fracture pattern in this study. Although posterior facet displacement was reported to be the key prognostic factor

in treating calcaneal fractures [12], displacement of the anterolateral fragment was also emphasized to be related to the loss of longitudinal calcaneal length and subtalar motion. The theoretical importance of this anterolateral fragment in surgical treatment are: 1) alignment of the intra-articular component of a calcaneocuboid joint fracture and possibly the anterior facet, 2) restoration of lateral length, 3) restoration of normal calcaneal shape and therefore help in properly aligning the calcaneocuboid joint in relation to the remainder of the calcaneus. Correction of these factors would better align the calcaneocuboid joint with the talonavicular joint, therefore potentially improving midfoot motion. For optimum results in the treatment of displaced intra-articular fractures, the normal anatomy of the joint must be restored, and movement of the joint must be resumed early. The greater initial biomechanical strength and stiffness may allow an earlier range of motion of the subtalar joint; a faster time to fusion may also be expected with more stable fixation techniques. The screws perpendicular to the fracture plane can provide the best inter-fragmental fixation. Therefore, a longitudinal screw is reasonable for attaining a better fixation of the transverse primary fracture. Our results indicate that the transverse primary fracture line of the calcaneus is the failure site after simulated open reduction and internal fixation under biomechanical testing. A lateral plate and parallel screws in the latero-medial direction cannot adequately stabilize the transverse primary fracture line. Adding a longitudinal transfixing screw can enhance the fixation strength significantly in the presence of a transverse primary fracture line and is recommended in clinical use.
From the above three studies, it was concluded that the impact method is an excellent experimental technique for producing tissue failure and/or fractures for further orthopedic research.

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