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Lab resource

Design and testing of a controlled electromagnetic spinal cord impactor for use in large animal models of acute traumatic spinal cord injury

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ABSTRACT

Background: Spinal cord injury (SCI) causes debilitating neurological dysfunction and has been observed in warfighters injured in IED blasts. Clinical benefit of SCI treatment remains elusive and better large animal models are needed to assess treatment options. Here, we describe a controlled electromagnetic spinal cord impactor for use in large animal models of SCI.
Methods: A custom spinal cord impactor and platform were fabricated for large animals (e.g., pig, sheep, dog, etc.). Impacts were generated by a voice coil actuator; force and displacement were measured with a load cell and potentiometer respectively. Labview (National Instruments, Austin, TX) software was used to control the impact cycle and import force and displacement data. Software finite impulse response (FIR) filtering was employed for all input data. Silicon tubing was used a surrogate for spinal cord in order to test the device; repeated impacts were performed at 15, 25, and 40 Newtons.
Results: Repeated impacts demonstrated predictable results at each target force. The average duration of impact was 71.2 ± 6.1 ms. At a target force of 40 N, the output force was 41.5 ± 0.7 N. With a target of 25 N, the output force was 23.5 ± 0.6 N; a target of 15 Newtons revealed an output force of 15.2 ± 1.4 N. The calculated acceleration range was 12.5–21.2 m/s^2.
Conclusions: This custom spinal cord impactor reliably delivers precise impacts to the spinal cord and will be utilized in future research to study acute traumatic SCI in a large animal.
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1. Background

Acute spinal cord injury (SCI) is a devastating event that often leads to permanent, debilitating neurological dysfunction. Approximately 12,000 Americans suffer acute SCI each year, and there are approximately 300,000 people living with the long term sequelae of acute SCI [1]. Researchers have made great strides in understanding the mechanism and pathophysiology of acute SCI. However, despite decades of intense research, few treatment strategies have led to clinical benefit for patients and many questions remain regarding the physiology of spinal cord injury and the optimal treatment of acute SCI.

The great majority of laboratory research into SCI has been conducted in small animal (rat, mouse, rabbit, etc.) models and a number of contusion impact devices have been developed for small animals. The NYU MASCIS impactor employs a weight-drop method to produce contusion SCI [2]. Originally developed for thoracic injury in rats, it has also been adapted for other small species and areas of the spine. The OSU impactor and Infinite Horizon impactor are computer controlled electromagnetic devices that were also developed for rats [3,4]. Recently, an air gun device has also been developed for SCI in rodents [5]. While much has been learned from small-animal studies using these devices, the ability to translate potential treatments from the "bench to bedside" remains lacking. This could be due to interspecies differences between humans and these smaller animals with respect to neurological injury response, recovery, and repair. Indeed, many researchers from the SCI community have called for more investigation in large animal models, in the hope that the injury response in these animals would be more similar to that observed in humans and treatments may emerge [6–8].

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Several authors have undertaken SCI studies in larger animals, including pigs, dogs, and sheep, and observed recovery and injury patterns that are similar to those observed in humans [9–20]. However, the injury mechanism in these models is highly variable, and includes balloon compression, aneurysm clip application, weight-drop, servo-motor compression, and pneumatic cylinder impact. While all of these methods are capable of producing SCI, they are also associated with some drawbacks. Compression type methods (balloon, clip, servo-motor) fail to replicate the contusion-type SCI from traumatic spinal column fracture and/or dislocation. These methods cannot reproduce the acceleration seen in acute traumatic injuries. The weight-drop method effectively creates a contusion injury, but the duration – or dwell time – and acceleration of impact cannot be varied and multiple impacts can be produced if the impactor bounces. Furthermore, none of these impact methods or animal models have been employed in a ventral impact model of SCI, which is the site of the spinal cord injury in burst fracture and other common traumatic injuries.

In light of these potential shortcomings and perceived needs from the community of SCI researchers, we set out to design, build, and test a prototype computer controlled electromagnetic spinal cord impactor for use in large animal models. Ideally, this device would be capable of reliably reproducing high acceleration impacts in a force-controlled fashion that could potentially improve upon other methods and closely approximate the contusion injury mechanism in SCI. We elected to test this impactor device on a spine model to demonstrate repeatability and characterize the impacts produced prior to *in vivo* testing. This work is one task in an overall Department of Defense funded program to develop a high-fidelity large animal model of burst-fracture related SCI. Here we describe the design and testing of our unique controlled impactor device. At the completion of this design and testing phase, we will have developed a controlled impactor that is ready for use in novel large-animal models of SCI with ventral and/or dorsal injury mechanisms.

2. Methods

2.1. Impactor specifications

In order to design an automated computer controlled spinal cord impactor, we first sought to identify the performance parameters that would be required to replicate the conditions of SCI from contusion. Specifically, we had to know the range of force required to produce a full spectrum of SCI, the distance that any impactor would have to traverse (spinal canal diameter for maximum compression), and the duration of the impact to the cord. Because these parameters are difficult to know from actual human SCI, we relied on information from animal and cadaveric studies. Lee et al. developed a thoracic contusion model in a miniature swine using a weight drop method with a load sensor attached to an impactor tip [12]. Impacts exceeding 36.4 Newtons resulted in complete spinal cord injury on neurobehavioral testing. The maximum displacement necessary was determined by the maximal spinal canal diameter on radiographic and anatomical studies in other large animal SCI models, and was found to be 12–15 mm in the thoracolumbar spine [12,14]. The impact duration was determined from cadaveric studies of thoracolumbar burst fracture – a contusion spinal cord injury mechanism – by Wilcox et al. [21]. They employed potted calf spines and subjected them to high energy axial loading to show that the dynamic spinal canal compression in burst fracture occurred over a mean duration of 42 ms. Therefore, our new impactor design would be required to deliver an impact of 0–40 N over approximately 50 ms and travel up to 15 mm.

2.2. Impactor design and construction

With these parameters in mind, a custom designed impactor, mounting platform, and integrated self-retaining retractor system was fabricated and constructed from custom machined parts and commercially available components (Fig. 1A, B). The electromagnetic impact force was generated by a linear voice coil actuator [VCA] (GVCM-051-051-01, Moticont®, Van Nuys, CA, USA) and direct current servo motor control card (510 series, Moticont®) in a current-controlled feedback loop. The voice coil was selected because it is capable of rapid acceleration and precision control. An in-line 25-lb button load cell (FC22, Measurement Specialties, Fremont, CA, USA) and linear potentiometer (KTC-75, Phidgets Inc.®, Calgary, Alberta, Canada) were used to measure the system output force and displacement respectively. These devices were mounted in-line with the VCA so that any force or displacement generated during movement of the actuator would be measured.

Spinal cord impact was delivered by a detachable 5 mm (rostral-caudal) × 10 mm wide aluminum impounder tip attached to a 150 mm shaft, and guide (Fig. 2) that could be autoclaved (Fig. 2A, B). This impactor size was chosen because the thoracic spinal cord in research animals such as miniature pigs, sheep and dogs is approximately 8–10 mm wide. The mounting platform for the device attaches to four posts that can be adjusted to any height for a variety of midline surgical approaches and subsequent impacts, including any dorsal level of the spine, and ventral cervical or lumbar approaches. The retractor device also has interchangeable blades to accommodate multiple approaches.

The impounder tip is supported by a machined aluminum guide with plastic spacer, which is attached to the impactor drive mechanism housing (Fig. 2A). The impounder tip and shaft are constructed of lightweight aluminum and weigh only 10 g, which allow these elements to rest directly on the dura covering the target spinal cord location without causing SCI (Fig. 3). The entire impactor mechanism is mounted to a vertically oriented precision positioning sled so that the device can be secured above the target location and precisely lowered into place by turning the positioner wheel (Fig. 4). In order to establish the zero-point for spinal cord impact, the drive mechanism and housing are slowly lowered by

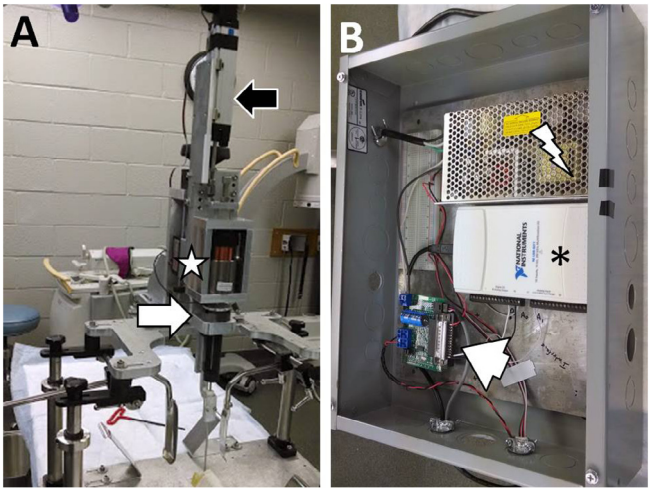

Fig. 1. Complete impactor device (A) with custom mounting system and self-retaining retractor. The voice coil actuator (star), button load cell (white arrow), and linear potentiometer (black arrow) are coaxially mounted to deliver and accurately measure force and travel distance. The control unit is shown in (B) with the power source (lightning bolt), data acquisition device (asterisk), and motor control card (arrowhead).