Improving Injury Severity Repeatability in an in Vivo Porcine SCI Model Through an Analysis of Spinal Cord Stiffness During Impact.

Amirhossein Borjali, Kitty So, Aysha A. Brown, Neda Manouchehri, Juliana Mitchell, Sigrun Jarlsdottir, Femke Streijger, Brian Kwon, Peter A. Cripton

I. INTRODUCTION

Spinal cord injury (SCI) models exhibit undesired variability in injury outcomes despite controlled impact conditions [1]. Conventional metrics such as peak force or displacement fail to correlate meaningfully with injury severity [2]. One of the most widely used indicators of injury severity is intraparenchymal hemorrhage (IPH) volume, which reflects the extent of tissue damage following spinal cord injury [3]. Synchronised force–displacement measurement provides a more physically meaningful framework, enabling the calculation of energy transfer and spinal cord stiffness. This study evaluates synchronised force–displacement analysis to derive energy and stiffness-based metrics and assess their relationship with IPH.

II. METHODS

A porcine SCI model (n ≈ 15) was used with a controlled weight-drop impact after dorsal laminectomy. The laminectomy window exposed the dura/spinal cord and was verified to allow the impactor tip to fall freely without bone contact. The guide rail was fixed to pedicle screws and positioned above the laminectomy with an articulating arm; the arm only positioned/aligned the rail and did not transmit load. After coronal/sagittal leveling, the impactor was released to fall vertically under gravity, with ventilation briefly paused to reduce motion. Thus, displacement represented impactor motion and compression of the dural sac/spinal cord complex relative to the stabilized vertebral column. Force was measured using a load cell (LLB215, FUTEK Advanced Sensor Technology, Irvine, CA, USA; capacity 222 N, nonlinearity ±0.5% of rated output, natural frequency ~31 kHz), mounted above the impactor tip. Displacement was recorded using a high-resolution magnetostrictive linear position sensor (BTL6-G500-M0102-PF-S115, Balluff Canada Inc., Mississauga, ON; measuring range 200 mm, repeatability ±5 µm, resolution ≤700 nA, sampling frequency 2 kHz). Velocity and acceleration were derived from displacement data using numerical differentiation. Force/displacement were acquired at 100 kHz and synchronized using the onset of tissue resistance, defined by increasing force and decreasing velocity.

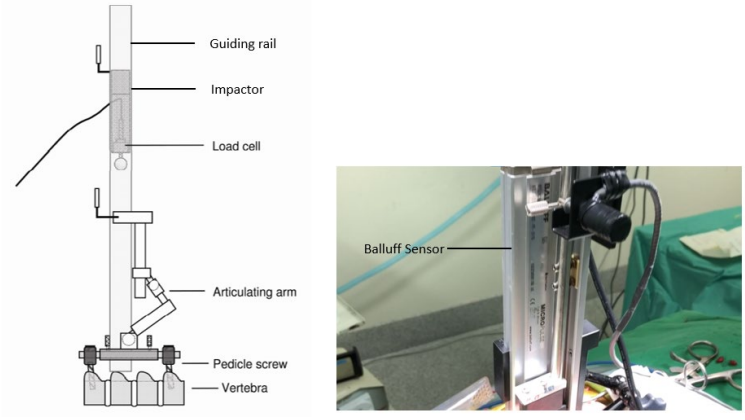

Fig. 1. Schematic of the impactor (left) and experimental setup illustrating the position of the Balluff sensor (right) used to measure compressive displacement and impact velocity.

A. Borjali is a PhD student in Biomedical Engineering at the University of British Columbia (UBC), Vancouver, Canada (corresponding author: amirb21@student.ubc.ca). K. So, N. Manouchehri and J. Mitchell are research staff at ICORD, UBC. F. Streijger is Lab Manager at ICORD, UBC. A. Allard Brown and S. Jarlsdottir are PhD students at UBC. B. Kwon is a Professor and orthopaedic surgeon at UBC. P. A. Cripton is a Professor at UBC.

Mechanical metrics included peak force, dural sac displacement (including the spinal cord, cerebrospinal fluid, and surrounding meninges), contact velocity, loading energy (area under the force–displacement curve during compression), hysteresis energy (difference between loading and unloading energy), unloading energy (limited elastic recovery during rebound), and mid-window stiffness (k_mid). IPH (%) was quantified as hemorrhage volume normalized by spinal cord volume.

III. RESULTS

Peak force showed a weak, non-significant tendency with IPH (R^2 = 0.08, p = 0.32), while displacement showed no relationship (R^2 = 0.01, p = 0.77). Contact velocity (R^2 = 0.12, p = 0.21) and loading energy (R^2 = 0.13, p = 0.20) were also not significantly correlated with IPH (p > 0.05). Hysteresis energy demonstrated similar behavior (R^2 = 0.11, p = 0.23). Among the measures investigated, the strongest association was observed for mid-window stiffness, k_mid (Figs. 2 and 3; R^2 = 0.45, p = 0.006), defined as the slope of the force–displacement curve within the approximately linear region of the loading phase (20–60% of maximum displacement), reflecting tissue resistance to compression. Thus, k_mid outperformed the other evaluated metrics in relation to IPH severity.

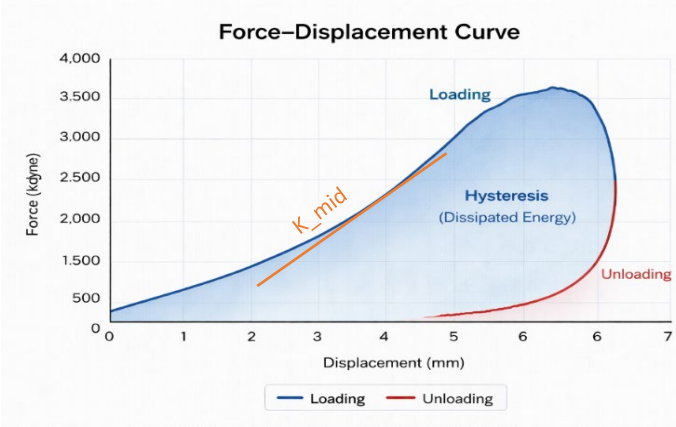

Fig. 2. Representative force-displacement curve; k_mid was calculated from the 20-60% maximum-displacement window and hysteresis energy from the shaded region.

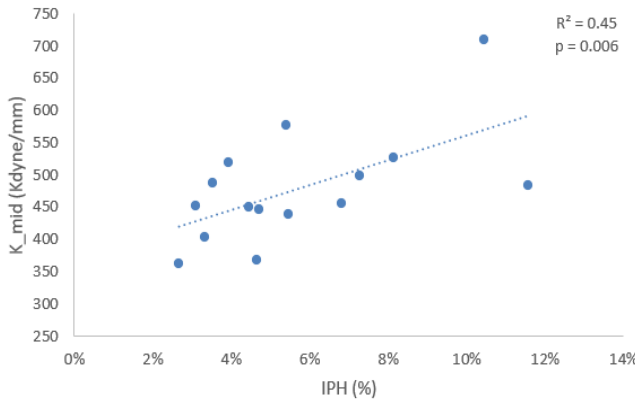

Fig. 3. Association between k_mid and IPH (R^2 = 0.45, p = 0.006). Higher mid-window stiffness was associated with greater normalized hemorrhage volume.

IV. DISCUSSION

Energy-based metrics improved upon peak-only measures by incorporating deformation history. However, in this dataset, k_mid outperformed the other evaluated metrics. Stiffness reflects tissue resistance to compression, whereas energy represents the total energy delivered to the tissue [4]. This delivered energy is distributed across multiple structures, including the dura, epidural fat, cerebrospinal fluid, and spinal cord, and therefore may not directly reflect the mechanical response of the cord itself. In contrast, stiffness, particularly within the mid-loading phase, may more specifically capture the cord–meninges complex response during compression, likely explaining its stronger association with IPH severity. Accurate synchronisation is critical, as misalignment distorts derived mechanical quantities, including stiffness and energy. Overall, this study suggests that stiffness-based metrics, particularly k_mid, may provide a promising and physiologically relevant indicator of SCI severity in this cohort compared with the other evaluated parameters. Further validation in larger datasets is required.

V. REFERENCES

[1] Kwon BK *et al*., J Neurotrauma, 2010. [2] Fiford RJ *et al.,* J Biomech, 2018. [3] Malomo T *et al.*, J Neurotrauma, 2022;39(23–24):1603–1635. [4] Panjabi MM, J Spinal Disord, 1992.