TIME AND TEMPERATURE SENSITIVITY OF THE HYBRID III LUMBAR SPINE

Duke BIOMEDICAL ENGINEERING

Duke INJURY BIOMECHANICS

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Introduction

- The standard Hybrid III (HIII) dummy has been used in a variety of environments and conditions that expose the ATD to multiple impacts in a relatively short time frame or in which test temperature is not easily controlled (e.g., Bass et al. 2007)
- When accelerations and forces are applied from beneath the dummy, the reaction of the lumbar spine dictates the forces and motion transmitted to the rest of the upper body. Hence the importance of characterizing the effects of temperature variations on the biofidelity and repeatability of the lumbar spine response
- In this study, compressive axial loading is used to investigate the HIII lumbar response to variations in temperature and the duration of rest between loading
- Bending involves the superposition of compression and tension. Therefore, in conditions that change compressive behavior, the bending behavior of the lumbar will also be affected
- The two aims of this study are to determine the influence of the duration of the rest interval between tests on the compression performance of the HIII lumbar; and to quantify the effect of temperature on the lumbar's compressive stiffness in temperatures relevant to indoor and outdoor testing

Methods

ATD-Environmental chamber setup

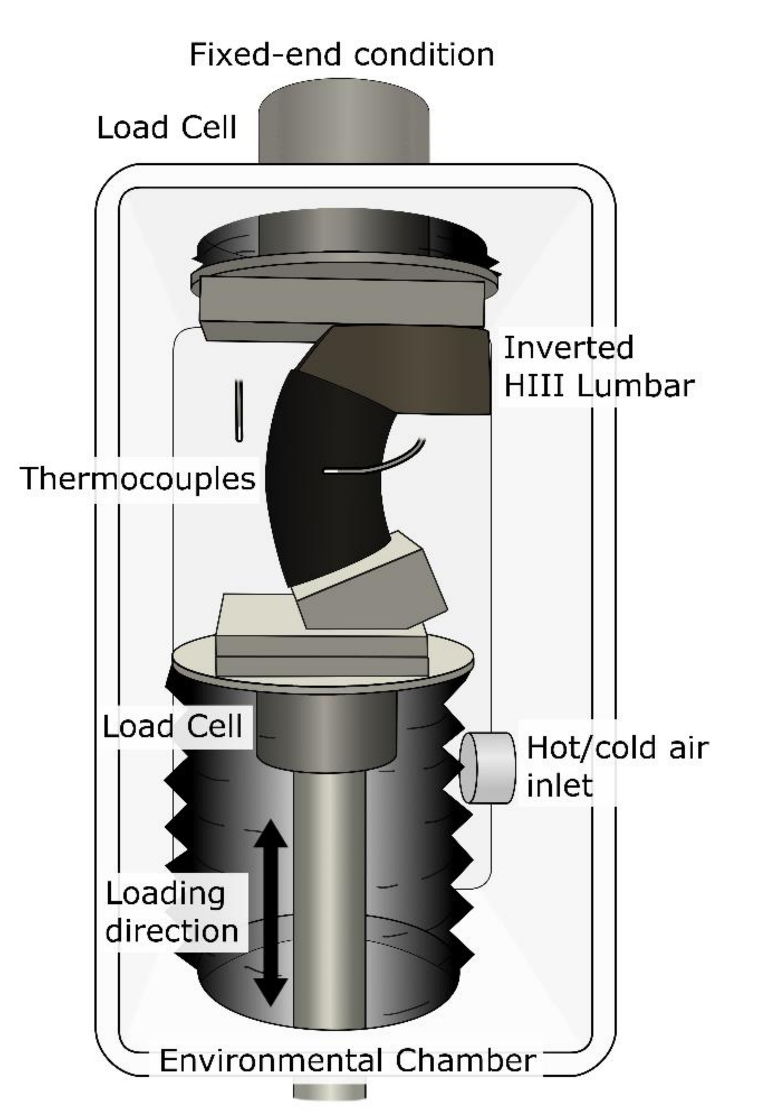


Figure 1. Test apparatus including environmental chamber.

The lumbar is mounted inverted so that the heavy pelvic bracket is on the stationary post. The load cells are protected by bellows from direct contact with the hot or cold gases in the chamber

Rest Duration Tests

- Carried out under temperature control at 25°C
- Input: 5.5 mm step and 10 second hold. Five repeats were conducted for each rest duration interval
- Resulting in: -5000 N peak force, -600 N/ms loading rate, 300 mm/s axial velocity, and force rise time of 10 ms
- Tested rest intervals: 120, 60, 30, 15, 10, 5, 2.5, and 1 minute

Temperature Tests

- 5.5 mm peak displacement at three loading rates

Rate	Loading Rate (N/ms)*	Velocity (mm/s)
Rate 1	200	140
Rate 2	400	220
Rate 3	600	300

*Results at 25°C. While the loading velocities were comparable between temperatures, the loading rate was subject to variation

- Each rate was repeated twice with a rest interval of 15 minutes
- Temperatures investigated: 12.5°C, 25°C, and 37.5°C

Rest Duration Tests Results

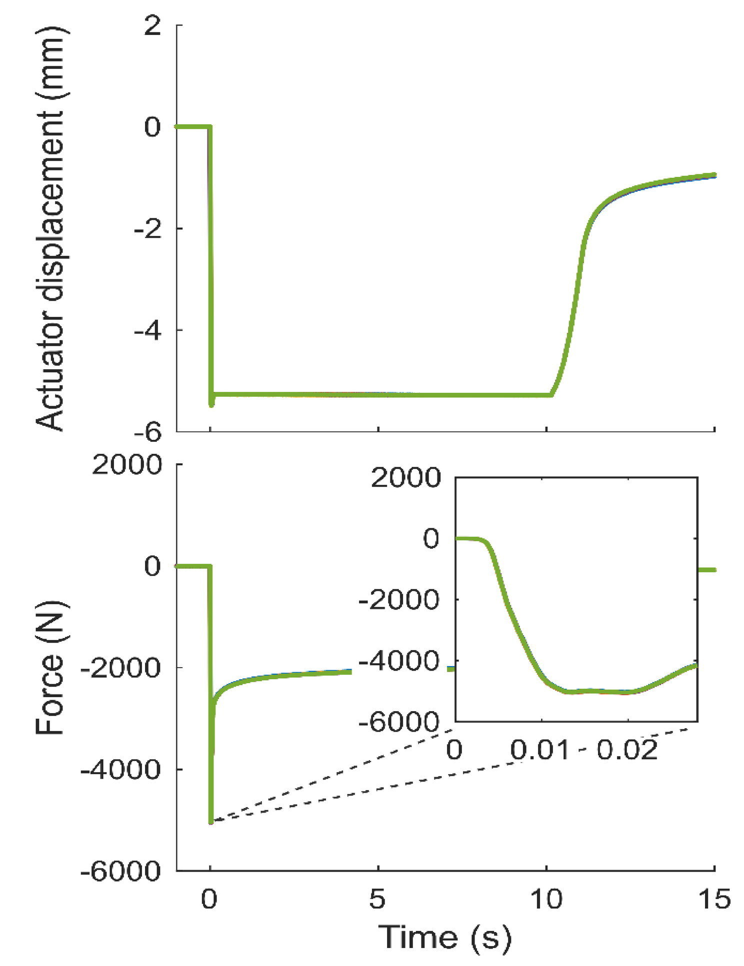


Figure 2. Traces of the displacement (top) and force (bottom) during the 5.5 mm displacement step-hold.

- During the duration battery, the general characteristics of the tests demonstrated excellent repeatability
- The time traces of the displacement input and force align well, and the shapes of the force traces, including bumps and waves, are nearly identical (Figure 2)
- In each plot, all 5 repetitions of the 2-hour interval tests are overlain. As seen in the magnified force trace, on this scale even small deviations in the traces were repeatable between tests
- There were, however, shifts in the magnitudes of these responses through the course of the series

- The amplitude of force, characterized by F_{3mm}, decreased throughout the test series, while creep steadily increased in magnitude (Figure 3)
- Overall, the change in F_{3mm} was modest at 174 N
- The creep reflects an increase in compression of 0.7 mm over the course of the duration battery
- Among duration groups, the magnitude of F_{3mm} decreased monotonically with decreasing rest duration, and differences between groups were analyzed with the LSMeans Tukey HSD test.
- Only two pairs – 15 min and 10 min; 10 min and 5 min – were not significantly different

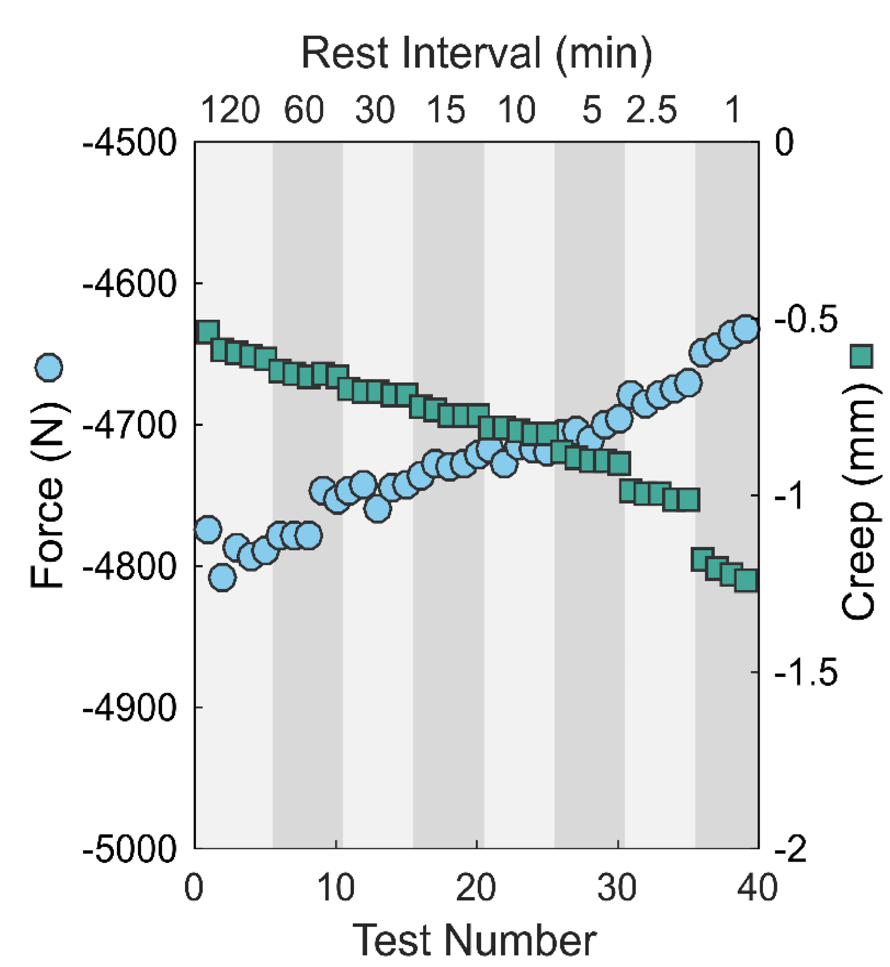


Figure 3. F_{3mm} and creep values from the duration tests. Tests are presented left to right in the order they were run, with bands separating the rest interval levels.

Temperature Tests Results

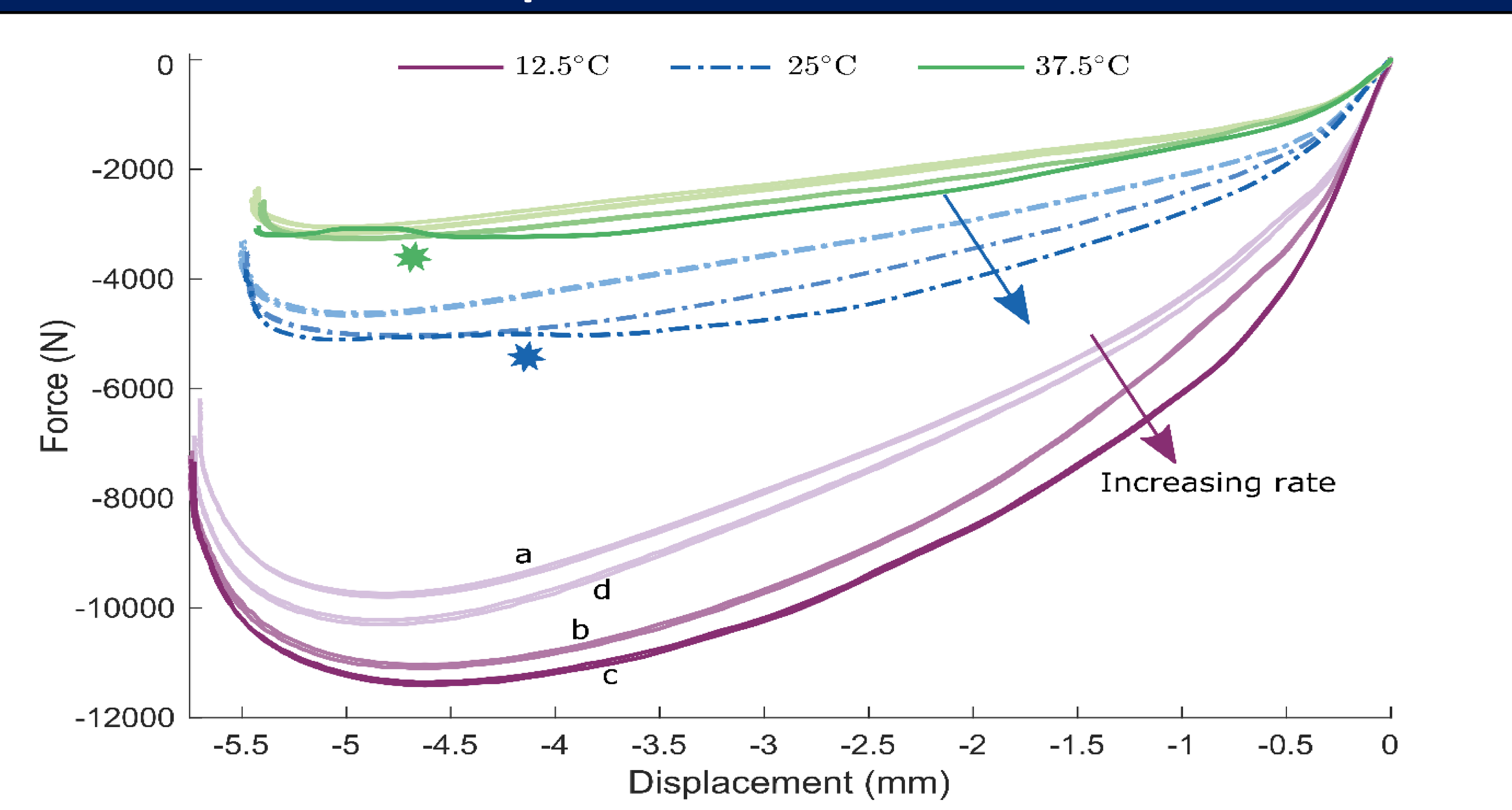
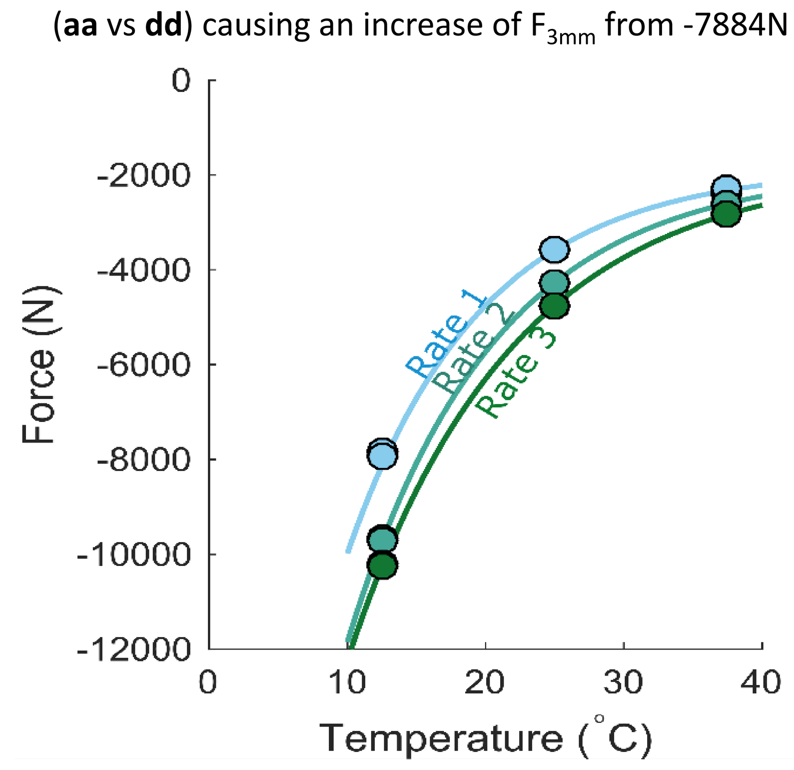


Figure 4. Force-displacement curves for each of the three rates at all three temperatures. Star symbols indicate Rate 3 trace regions with marked changes in behavior. The 12.5°C traces were not repeatable; each letter indicates a pair of tests, applied in the order **aa** – **bb** – **cc** – **dd**, where **a** and **d** represent identical Rate 1 inputs.

- Colder temperatures and higher rates were associated with increased stiffness
- Compared to the near-room temperature (25°C) condition, F_{3mm} at the highest rate decreased by 40% at the 37.5°C condition (-4754 N vs -2833 N)
- Compressive stiffness increased dramatically in the cooler condition; at 12.5°C, F_{3mm} increased by 115% to 10,216 N
- At 12.5°C the lumbar spine showed a stiffness increase of 5% between the first and second pair of Rate 1 (**aa** vs **dd**) causing an increase of F_{3mm} from -7884N to -8279N



- The relationship between F_{3mm} and temperature was characterized by a 3-parameter exponential model (Figure 5) of the form:

$$F_{3mm} = A + Be^{C\cdot T}$$

- The fit was performed by nominal rate, where:
  - F_{3mm} is the force at 3 mm displacement
  - T is temperature
  - A, B, and C are constants
- ANOM of the coefficients did not indicate any instance where a coefficient differed significantly from the mean by rate.

Figure 5. The relationship between F_{3mm} and temperature is modeled well with a 3-parameter exponential decay curve. Each rate is fit by a significantly different parameter set, with higher rates associated with higher force amplitudes.

Discussion

The duration tests indicated incomplete viscoelastic recovery at every interval at 25°C. Within each duration group, the F_{3mm} value decreased with test repetition. Of particular interest are the implications of the nonsignificant duration-repetition interaction term; this indicates that each test repetition decreased F_{3mm} nearly the same amount, regardless of the rest duration between tests. A single linear regression indicates that each test reduces the F_{3mm} value of the subsequent test by~3.8 N throughout the entire test battery. While each decrement is small, over the course of the 40 tests in this battery, the amplitude of F_{3mm} decreased of 174 N. Furthermore, there was no evidence that an asymptote in this behavior was being approached, and the net effect of this incomplete recovery may increase with additional tests. This incomplete recovery introduced a systematic error, rather than a random error, which could create false positives or false negatives in the data set.

The gradual softening of the spine during the 25°C duration tests is at odds with the stiffening observed in the 12.5°C temperature tests. The cool temperature series also exhibited markedly different creep behavior as compared to the duration tests (Figure 6).

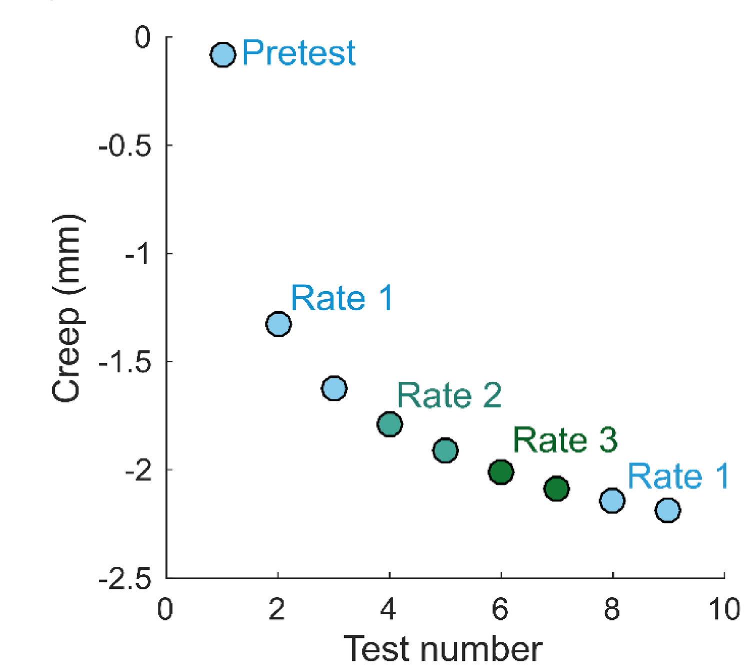


Figure 6. Creep values during the 12.5°C test battery.

At the cool 12.5°C temperature the total creep was almost twice as large at -2.11 mm when compared to the duration test battery. The data indicates that cooler temperatures increased the stiffness of the spine and increased peak loads. After exposure to higher loads, the creep recovery is diminished, leading to a shortened compliant height and higher strain levels. Perhaps in this regime, softening due to incomplete stress relaxation is offset by higher strain levels, leading to higher recorded forces.

The inconsistency in compressive loading shape as shown in the flattened areas in Figure 4 also presents an obstacle for experimenters. In ATDs subjected to vertical loading (Gowdy et al. 1999), a similar flattened peak appears in the lumbar force trace for the curved Hybrid III spine. From the current study, there appears to be a buckling mode that is only observed under certain combinations of rate and temperature and that it is not predicted by a force or displacement threshold. With that unpredictability, peak force becomes a poor descriptor of the severity of the loading.

The temperature effects in the lumbar are very strong. While the stiffness of the HIII neck increased 115% at 0°C compared to near-room temperature (Schmidt et al. 2018), the lumbar saw the same stiffness increase at 12.5°C. To an even greater extent than the neck, the HIII lumbar spine's characteristics require investigators to be cognizant of temperature as a confounding variable.

Conclusions

- No recovery period of 2 hours or less will allow complete viscoelastic recovery of the HIII lumbar spine under the weight of the dummy's upper body at near room temperature
- Temperature effects were pronounced, resulting in compressive force differences of 261% over the range of 12.5° to 37.5°C. Compared to the stiffness of the lumbar at 25°C, the stiffness at 37.5°C fell by 40%; at 12.5°C, the stiffness more than doubled, increasing by 115%. The magnitude of these effects was rate-dependent.
- Only a modest decrease in temperature is necessary to dramatically change the response and repeatability of the lumbar in compressive loading. The large magnitude of the temperature effect has severe implications in its ability to overwhelm the contributions of targeted test variables.
- Care must be taken to control for the effects of temperature throughout testing, even in indoor laboratory environments. When reporting results from the HIII lumbar, the temperature should also be reported.

References

- Bass C, Salzar R, Ash J, et al. Dynamics models for the assessment of spinal injury from repeated impact in high speed planing boats. Paper presented at: Proceedings of the International Research Council on the Biomechanics of Injury conference 2007.
- Gowdy V, DeWeese R, Beebe MS, et al. *A lumbar spine modification to the hybrid iii atd for aircraft seat tests.* SAE Technical Paper;1999. 0148-7191.
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