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Accounting for Frame and Fixation Compliance in Cervical Spine Tensile Testing

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ABSTRACT

Tensile testing of the human cervical spine involves some unique instrumentation challenges. Because of the curvature of the neck, even simple tensile testing results in combined loading. In order to understand and characterize this loading, the test apparatus may need to be fairly complex. Historically, reported stiffnesses from load-displacement data have assumed that the compliances of the test frame and the casting do not intrude on the measured response. However, because of the relatively high stiffness of spine specimens and the complexity of the test apparatus, this is not necessarily the case.

In this study, 17 specimen preparations were tested in tension under a variety of end conditions. Tests were performed on whole spines and on individual motion segments. On average, the stiffness of the motion segment preparations was 257 N/mm, and the stiffness of the whole cervical spine was 48 N/mm. The test frame was found to have a stiffness of 933 N/mm. Assembling a whole spine from a series combination of 8 motion segments with a stiffness of 257 N/mm results in a whole spine stiffness of 32.1 N/mm (32% error). The actual motion segment stiffness can be calculated by assuming that the preparation stiffness is a series combination of the stiffnesses of the motion segment and the frame. Applying this correction to the segments in this study results in an actual motion segment stiffness of 356 N/mm. Taking the frame compliance into account, the actual whole spine stiffness is 51 N/mm. A series combination of 8 motion segments using the corrected stiffnesses results in a whole spine stiffness of 45.0 N/mm (12% error).

We conclude that the compliance of the frame and the fixation must be quantified in all tension studies of spinal segments. Further, reported stiffness should be adjusted to account for frame and fixation compliance. This may not be possible for existing spine data in the world literature due to an absence of data on individual test frame compliance.

INTRODUCTION

There have been numerous studies of the mechanical properties of human cervical spine segments. These have included testing in a variety of loading conditions including compression, bending, tension, and combinations of all three. These tests form the basis of current understanding of cervical spine tolerance and injury mechanisms. In addition, the data from these tests is used to develop computational models for further research and to develop interventions to reduce the frequency and severity of neck injuries.

Since human tissue is difficult to procure, and since spine data is very important, most biomechanical testing is designed to maximize the utility of each test specimen (McElhaney *et al.*, 1983; McElhaney *et al.*, 1988; Moroney *et al.*, 1988; Pintar *et al.*, 1989; Pintar *et al.*, 1990; Myers *et al.*, 1991; Nightingale *et al.*, 1996; Nightingale *et al.*, 1997; Van Ee *et al.*, 2000; Ching *et al.*, 2001; Yoganandan *et al.*, Oct, 1991). This necessarily requires the use of complex test apparati. When stiffnesses are reported from load-displacement data, it is generally assumed that the compliance of the test frame and the casting compliance do not intrude on the measured response. However, because of the relatively high stiffness of spine specimens, and the complexity of the apparatus, this is not necessarily the case. Few biomechanical studies of the cervical spine have reported frame compliance, and none have had the ability to directly compare the stiffness of the whole spine with the stiffness of a cervical spine model that is based on results from testing of sectioned specimens.

Computational modelers and ATD designers must be particularly cautious when using motion segment data to construct models of the whole spine. Any errors in the motion segment stiffness properties are compounded when the motion segments are assembled into a whole spine model. As a result, relatively small errors in the motion segment data can produce large errors in the whole spine response. Accordingly, the purpose of this study is to examine the effect of frame and fixation compliance on the stiffness data from tensile testing of cervical spine segments. Sources of compliance are identified and methods to correct the data are proposed.

METHODS

Testing was performed on 17 unembalmed male cadaver specimens from the head through T2. The average age of the specimens was 58±9 years. The tests were conducted in two parts: the first series was performed on whole spine specimens (T1 through head), and the second series was preformed on sectioned specimens. The results are divided into the following groups: whole-spine, C6-C7, C4-C5, and Head-C3. All whole-spine testing was non-destructive, and the sectioned groups included failure tests.

The test apparatus was designed to accommodate whole spines and sectioned spines, and to allow testing using a variety of mechanical end conditions (Figure 1). An RVDT located at the rotational bearing quantified head rotation. LVDTs were used to monitor the hydraulic actuator position and the linear bearing position. Either of the two cranial degrees of freedom (AP translation and rotation) could be locked to examine the effect of end condition. A six-axis Denton load cell coupled the caudal end of the spinal segment to an MTS hydraulic actuator. Data were collected using a digital data acquisition system (National Instruments; Austin, TX). Test imaging was done in the sagittal plane using a CCD camera at a frame rate of either 5 or 50 fps.

Specimens were cast using heavy gauge pedicular loops traveling from the casting material through the spinal canal over the pedicle and back through the vertebral foramen. In addition, k-wires and fiber reinforced acrylic were used. For the upper cervical segment, two vertebrae (C2, C3) were cast using a combination of bone screws and k-wires pre-molded into fiber reinforced acrylic.

Once the specimens were mounted in the test frame, a battery of tests was conducted to evaluate the effect of end condition and load line-of-action. The details of the battery can be found in Van Ee et al, 2000. The data presented in the Results section of this study are from stiffness tests conducted with a fixed rostral end-condition. These tests were run under force control at a rate of 50 N/s to a peak of 200 N. The upper cervical spine specimens were positioned with the Frankfort Plane horizontal.

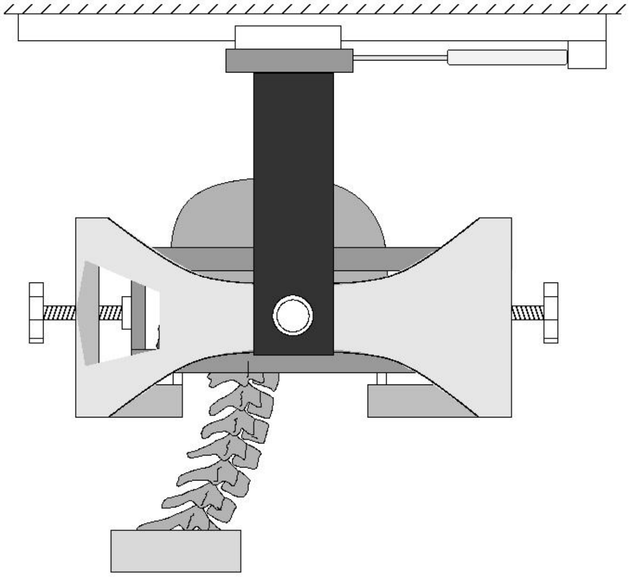

Figure 1: The specimen is held in a cradle that allows translation and rotation of the rostal end. These degrees of freedom can be locked. The position of the superior end of the specimen can be adjusted relative to the rotational bearing to change the line-of-action. The specimen is loaded by downward translation of the hydraulic actuator, which is coupled to T2 via a 6-axis load cell.

The force-displacement results from individual specimen test (whole-spine and segments) were regressed using a standard linear stiffness model and a logarithmic model of the form:

$$x = \frac{1}{B}\ln\left(\frac{F}{A}+1\right) \tag{1}$$

where A and B are constants and F and x are the tensile force and displacement, respectively. An average response and standard deviation for each type of segment was calculated and the resulting curve was fit with the logarithmic model.

The compliance of the test frame was determined by testing a block of hardwood (oak) with the same protocol used for the spine segments. A 3.31 x 3.81 x 7.14 centimeter block was wired in the same manner as the human vertebrae and was cast using the same materials. The wood specimen was preconditioned and then tested 30 times. The force-displacement results were regressed to determine the linear stiffness, and the stiffness values for all 30 trials were averaged. The stiffness functions for the whole spine and the segment tests were then corrected using the results from the oak tests.

RESULTS

Uncorrected Stiffness Results

The force-displacement responses for all three segments are shown in Figure 2. The lower cervical spine motion segments are of similar stiffness. The upper cervical spine segment is less stiff, primarily because it is a series combination of the C1-C2 and Head-C1 segments. Coeffecients for the linear and log models of these responses are shown in Table 1. The force-displacement response for the whole cervical spine is shown in Figure 3.

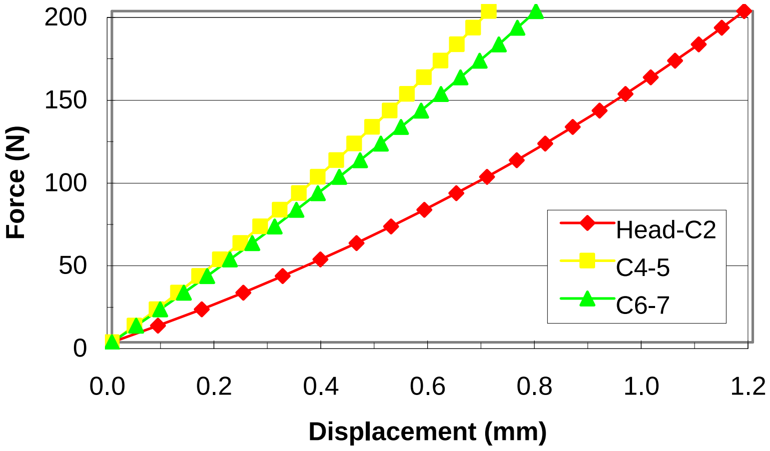

Figure 2: Uncorrected force-displacement results for cervical spine motion segments. These curves are calculated from the log functions in Table 1. Note that 200 N produces < 0.8 mm of displacement C4-C5.

Table 1. Coefficients for the Uncorrected Models.

		O-C2	**C4-C5**	**C6-C7**	**Whole Spine**
Log Model	A	174.2	447.9	601.1	107.4
	B	0.646	0.523	0.362	0.286
Linear Model	K	155 N/mm	271 N/mm	243 N/mm	48 N/mm

Since the whole spine response is simply a series combination of the responses of the motion segments, it should be possible to reconstruct the whole spine response from the segment tests. This was done by summing the compliance functions for 3 C4-C5 segments, 3 C6-C7 segments, and the Head–C2 segment (Equation 2). The results from this function are shown in Figure 3.

$$x_{whole} = \frac{3}{B_{45}} \ln\left(\frac{F}{A_{45}} + 1\right) + \frac{3}{B_{67}} \ln\left(\frac{F}{A_{67}} + 1\right) + \frac{1}{B_{O2}} \ln\left(\frac{F}{A_{O2}} + 1\right) \tag{2}$$

As can been readily seen from Figure 3, the reconstructed whole spine stiffness is considerably less stiff than the measured whole spine response. Although minor differences between the two curves are expected, the error in the reconstruction indicates that the uncorrected motion segment data is not suitable for the prediction of the whole spine responses.

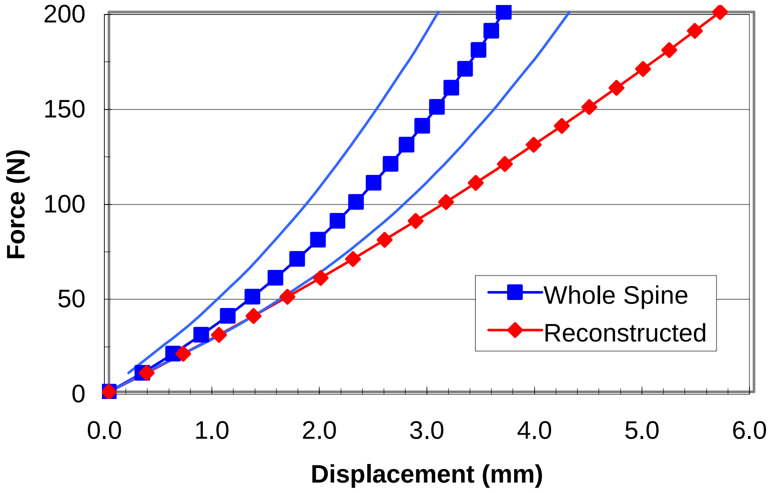

Figure 3: The average response of the whole cervical spine in a tension test with fixed end conditions (the corridor is ± one standard deviation). Also shown is the response of a whole cervical spine model based on a reconstruction from the motion segment data in Figure 2.

Testing with the oak block resulted in an average frame stiffness of 933 N/mm with a standard deviation of 21 N/mm. The test frame stiffness (K_{comp}) was linear (R^2=0.998). This stiffness value accounts for the stiffness of the casting material, the stiffness of the test apparatus, and the stiffness of the fixation wires. It does not account for the stiffness of the vertebra and the stiffness of the contact interface between the wires and cortical bone.

Corrected Stiffness Results

The flexibility functions were corrected by subtracting the displacement due to frame compliance from the nonlinear flexibility functions. For the whole spine, the flexibility is given by:

$$x = \frac{1}{107.4}\ln\left(\frac{F}{0.286}+1\right)-\frac{F}{K_{comp}} \tag{3}$$

The segment stiffnesses were similarly adjusted and the adjusted functions were fit a second time with both a linear and non-linear model. The coefficients for the corrected fits are given in Table 2.

A reconstruction of the whole spine response from the corrected segment responses is given by:

$$x_{total} = \sum_{i=1}^{n}\left[\frac{1}{B_i}\ln\left(\frac{F}{A_i}+1\right)\right]-\frac{nF}{K_{comp}} \tag{4}$$

Equation 4 is a compact form of Equation 2 and includes a compensation for frame stiffness. The results from this function are shown in Figure 4. A linear regression of Equation (4) results in a stiffness of 45 N/mm. This is 12% lower than the 51 N/mm from the whole spine test.

Table 2. Coefficients For the Corrected Models.

		O-C2	C4-C5	C6-C7	Whole Spine
Log Model	A	125.9	268.9	389.7	96.2
	B	0.97	1.11	0.70	0.32
Linear Model	K	186 N/mm	382 N/mm	329 N/mm	51 N/mm

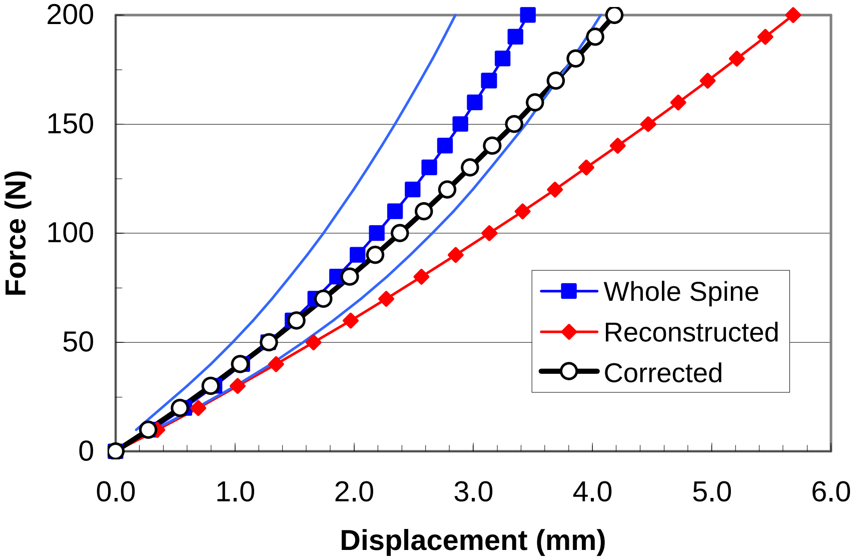

Figure 4: This Figure is the same as Figure 3, but with the addition of the reconstruction of the whole spine response using corrected motion segment data. The adjusted response is much closer to the measured response of the whole spine.

CONCLUSIONS

This study demonstrates that it is not possible to reconstruct whole cervical spine responses directly from motion segment data without significant error. This is primarily due to the fact that human cervical spine motion segments are remarkably stiff in tension. As a result, stiffnesses derived from motion segment tests are susceptible to error from all the compliant structures in the load path. These include the specimen fixation, the casting materials, and most importantly, the test apparatus. With careful characterization of the test frame, it is possible to correct the motion segment data, but not completely.

In correcting the errors associated with frame compliance, there were a number of limitations. The first is that we assumed that the C4-C5 and C6-C7 motion segments were representative of all eight motion segments. Another limitation is that we did not characterize the compliance at the bone-wire interface of the fixation. Finally, we did not account for the effects of cutting both the anterior and posterior longitudinal ligaments (ALL and PLL). Anatomical studies have shown that the deepest fibers of these ligaments span only one joint; however, the more superficial fibers span multiple joints (Kazarian, 1981; Lang, 1993). Therefore, sectioning of the cervical spine may introduce some non-physiological compliance into the motion segment.

It is noteworthy that the test frame errors in motion segment testing are not random - they consistently result in underestimates of stiffness; therefore, they accumulate. However, this accumulation is linear – a 12% error in segment stiffness will result in the same error for the whole spine reconstruction. Figure 5 shows a plot of the accuracy of motion segment stiffness as a function of the stiffness of the test frame. If the frame is 50 times stiffer than the specimen, we can expect a 2% error in the segment stiffness and a corresponding 2% error in whole spine stiffness

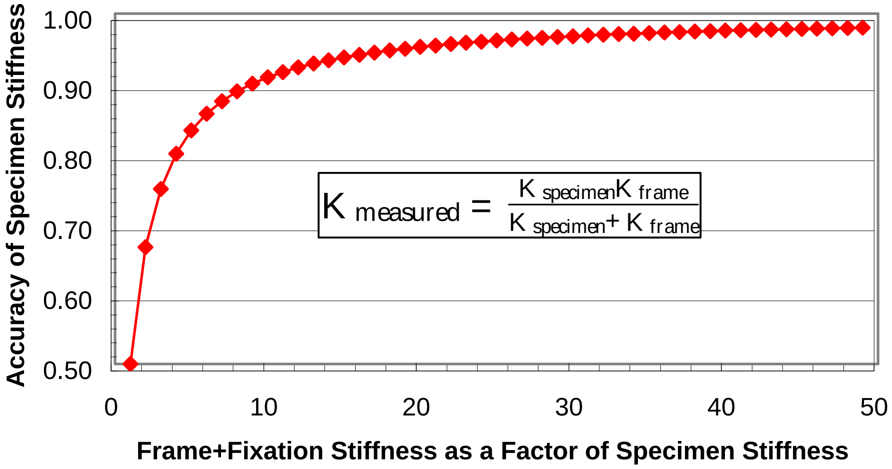

Figure 5: Accuracy of specimen stiffness as a function of frame stiffness. If the frame is 10 times stiffer than the specimen, then there is a 10% error (90% accuracy) in the specimen stiffness. If the frame is 50 times stiffer, we can expect an accuracy of 98%.

Although it may not be possible to entirely correct the motion segment data, it is still possible to produce a highly biofidelic whole spine model from motion segment results. Since the motion segment tests accurately reflect relative stiffnesses and ranges of motion, it is reasonable to scale the motion segment results to achieve a match between the model and the whole spine test.

The results from this study indicate that the compliance of the test frame should be either accounted for or reported in all testing of cervical spine motion segments. This is the only study that we are aware of that tests the whole cervical spine and its component motion segments. This study is unique in that it was possible to compare the stiffness of the whole spine with the stiffness of a reconstruction from motion segment data.

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DISCUSSION

PAPER: **Accounting for Frame and Fixation Compliance in Cervical Spine Tensile Testing**

PRESENTER: ***Dr. Roger Nightingale, Duke University***

QUESTION: *Guy Nusholtz, DaimerChrysler*
The way I read what you're saying–is more a clarification–is you have a number of apparatus structures and each of them is very stiff, and what you're doing is by themselves, they might not make a big difference. But when you add up all of the different little, tiny things that go into these differences, it adds up to something which is significant.

ANSWER**:** That's right.

Q: About how much stiffer would each of the individual material properties, or stiffnesses have to be so it doesn't make a difference? A hundred or a thousand times what the modulus is, the material that you're looking at?

A: Actually, I did a plot of: If your frame is 20 times stiffer than your specimen–And by frame, I mean all of these summed stiffnesses, you're going to expect 5% error. If you're 50 times stiffer, you've got a 1% error. So, I'd have to go back and actually run the numbers on it, but I don't think we'd really have to be, you know, all that much stiffer. But I think within the limitations of what we're trying to do with this apparatus, we're going to have some amount of frame compliance that we're going to have to account for.

Q: So, you won't be able to set up a guideline that says, 'The frame has to be this much stiffer and then you can ignore it." You're going to have to take into account the stiffness of the apparatus, given the way we test stuff now, every single time.

A: I think certainly for cervical spine motion segments because they're stiff. I mean, we're getting almost 400 newtons per millimeter in a fixed test on a C-4/5 motion segment, and that's pretty stiff. I mean, we've got–You saw the apparatus it's fairly robust, and we're still getting, you know, with the play that we have in our end conditions, we're still getting enough displacement to affect our results. 200 microns when you look at it, but that's enough.

Q: Thank you.

Q: *Erik Takhounts, NHTSA*
I was wondering if it would be easier, actually, to take one motion segment and measure actually displacements between the bones in one test and to compare that to the stiffness of the whole thing?

A: So, you could put a clip gage across the disk, potentially, and do a measurement that way, and that might be something that's worth, that's worth looking at. A difficult instrumentation challenge in an already difficult test, but I think it's probably something that's worth looking at.

Q: When you backed up the stiffnesses, did you also stiffen up the response of the whole spine?

A: Yeah. We went from 48 newtons per millimeter to 51, but it's not a big difference there because the whole spine's fairly compliant, and we only have one factor, one frame factor to take into account. When you have a stiff motion segment and you're adding up eight frame factors, it really starts to build–the error does.

Q: Thanks.

Q: *David Nuckley, University of Washington*
Hi. Did you do–Your motion segments were all single-function spinous networks that were fixed, like, in a fixed fix.

A: Right.

Q: And, you put your oak in there. Did you put your oak in your yoke assembly and test the compliance of that because I'm just wondering if that whole bearing assembly may have a different compliance that you could apply to that equation either to your fixed fix, and that may be another...?

A: Well, in order–

Q: The reason you're not getting as close as you thought?

A: Well, I should have been clearer in my methods. That yoke assembly in order to minimize as many variables as we can, is in every test. So when we do a motion segment test, what we do is we pass a bar down through the yoke assembly and attach our specimens in there. So, it's always in there.

Q: Okay. Thank you.