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Methods for Dynamic Material Testing of Human Cortical Bone Specimens

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ABSTRACT

A number of researchers have investigated the material properties of human cortical bone and the effects of different parameters such as: tension, compression, age, bone density, direction dependence, regional variation, and rate dependence. Although all of the aforementioned parameters have been investigated, previous studies have focused on the long bones of the body and none have addressed more than two or three of these parameters within a single controlled study. In addition, material property testing of human cortical bone is also desirable to obtain the material properties of a specific body in order to model specific tests conducted with that body. Therefore, there is still a necessity for continued material property testing of the human skeletal system. The purpose of this study was to develop a method for preparing and testing human cortical bone coupons at dynamic rates in both tension and compression to obtain accurate, comprehensive material property data. The methods presented in this paper were developed through 195 practice tests on human tibia cortical bone. A detailed specimen preparation technique was developed to obtain cortical bone test specimens while maintaining proper specimen alignment and hydration. Methods to minimize the effects of bending due to misalignment of the test setup and test specimens were addressed. The use of a slack adapter provided constant strain rates. A strain gage, potentiometer, extensometer, laser vibrometer, and the MTS internal LVDT were evaluated for displacement measurement accuracy under static and dynamic loading. The laser vibrometer, which has nanometer scale accuracy and a high frequency response of 200 kHz, was found to be the best displacement measurement device when testing at dynamic rates. The results of the coupon tests conducted on human tibia cortical bone proved that the specimen preparation and test methods presented in this study are both accurate and precise for determining cortical bone material properties.

INTRODUCTION

There have been numerous studies that have invested the material properties of human cortical bone and the effects of different parameters such as: tension, compression, age, bone mineral density, direction dependence, regional variation, and rate dependence. Dempster (1952) presented one of the first studies using human femur and tibia bones. This study conducted tension and compression tests in both the axial and lateral directions, but only quasi-static loading rates were tested. Therefore, viscoelastic effects needed for application to the automobile safety field were not investigated. Evans (1956) performed tests on human femur, tibia, and fibula cortical bone specimens in tension and looked at the effects of regional variation. However, like Dempster (1952), these tests were conducted at quasi-static rates and did not examine viscoelastic effects. McElhaney (1966) presented tests on human femur bones in compression, but did not look at any tests in tension. Reilly (1975) performed tests on human femur specimens in tension and compression and in three loading directions. However, this study was limited also to only quasi-static loading rates and did not perform high-rate loading tests. Finally, Saha (1974) conducted dynamic tests but only in the tension and axial directions.

Although all of the effects of the aforementioned parameters have been investigated, previous studies have focused on the long bones of the body and none have addressed more than two or three of these parameters within a single controlled study. In addition, material property testing of human cortical bone is also desirable to obtain the properties of a specific body in order to model specific tests conducted with that body. Therefore, there is still a necessity for continued material property testing of the human skeletal system. The purpose of this study was to develop a method for preparing and testing human cortical bone coupons at dynamic rates in both tension and compression to obtain accurate, comprehensive material property data.

METHODS

The methods for dynamic material testing of human cortical bone presented in this paper were developed through 195 practice tests on human tibia cortical bone, and are presented in four sections: specimen preparation, detailing proper alignment and hydration issues; alignment of test setup, detailing specimen and grip centerline conformance; slack adapter, detailing advantages and operation; and evaluation of displacement measurement devices, detailing advantages and disadvantages of each.

Specimen Preparation

In order to conduct material property testing on human cortical bone, the bone coupon must first be machined into a testable geometry. This was done through numerous steps of detailed preparation. First, an oscillating bone saw was used to make two cuts to separate the tibia from the body (Figure 1).

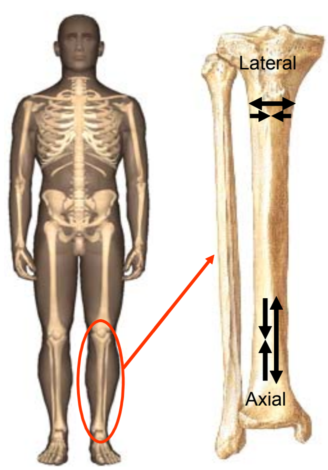

Figure 1: The tibia tests examined two orientations of cortical bone loading; therefore, two sets of specimens were harvested for axial and lateral directions.

The mid-diaphysis of the tibia was cut into sections using a low speed diamond saw with micrometer precision (Figure 2 B). The diamond saw blade was immersed in a saline bath to minimize the heat created from friction and maintain specimen hydration, which has been shown to significantly affect the material properties, specifically plasticity, of cortical bone (Burstien, 1972). Then, the sections cut from the tibia were placed in a bone chuck and two parallel cuts were made along the axis of interest to remove a rectangular section of the bone (Figure 2 C). Great care was taken when placing the bone sections in a bone chuck to ensure the axis of interest coincided with the axis of cutting. The rectangular cortical bone specimen was placed in a custom bone chuck, and a third cut was made to remove the cancellous bone from the piece. This cut also created a flat side that was placed faced down on the milling base (Figures 2 D and E). Finally, additional cuts were made to level the uncut side and, if necessary, trim the ends to fit on the milling base. It should be noted that the dimensions of the rectangular cortical bone specimens were cut slightly larger than the final specimen dimension to allow a clamping area for the milling process. Since the tibia is triangularly shaped, this process was repeated in order to obtain rectangular cortical bone specimens from all three sides of the tibia.

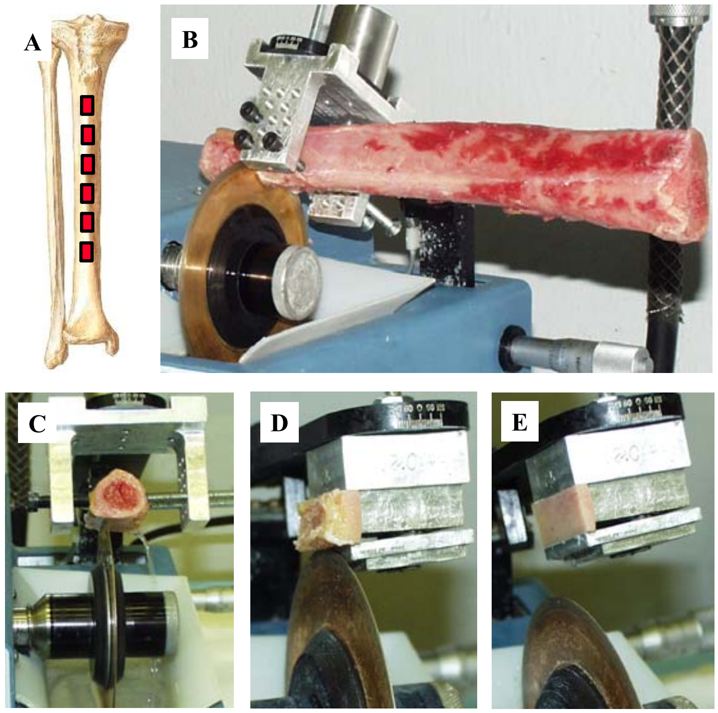

Figure 2: A) The tibia was removed from the body. B) The mid-diaphysis of the tibias was divided into several smaller sections. C) Two parallel cuts along the axis of interest were made on the diamond saw to obtain a rectangular section of bone. D) Another cut was made to isolate the cortical bone from the cancellous bone. E) The resulting rectangular cortical bone specimen had one flat side to place face down on the milling base of the CNC.

The resulting rectangular cortical bone specimen was then milled to the final test specimen dimensions using a small Computer Numerical Control (CNC) machine (MAXNC 10, MAXNC Inc., Chandler, AZ) (Figure 3). A rectangular pocket was milled into a plastic milling base to create a surface parallel to the z-axis, or vertical axis, of the mill. The flat side of the rectangular cortical bone specimen was placed on the plastic milling base. This was done to assure that the top face of the cortical bone specimen was milled parallel to the flat face. Again, great care was taken when placing the cortical bone specimen on the milling base to ensure the axis of interest coincided with the axis of the mill. The milling base was placed in a saline bath to minimize heat and maintain specimen hydration.

Two sets of grips were used to ensure the specimen did not slip during the milling process, which would result in asymmetric machining of the test specimen. For the dog-bone shaped coupons used for tension testing, one set of grips held the sides of the specimen while the pin holes, top face, and ends were milled (Figure 4). After the first CNC program was run, a second set of grips was clamped on the specimen while the first grips were still in place. The second set of grips held the specimen in place while the dog-bone contour was milled (Figure 4). For the rectangular compression specimens, a different two stage grip set was used to cut the coupon to the final dimensions. The final test specimen dimensions were based on both previous literature and ASTM standards for tension and compression material testing (ASTM Standard E

8M-01; ASTM Standard D 5026-01; ASTM Standard E 9-89a; Crowninshiel, 1974; Dempster, 1952; Reilly, 1975; McElhaney, 1966; Wood, 1971; Yueuheui, 2000) (Figures 5, 6, and 7). Finally the coupons were evenly sanded with 240, 320, 400, and 600 grit wet sand paper. The specimens were kept immersed in a saline solution and refrigerated until tested. Once the specimens were placed on the test setup, they were kept hydrated by spraying a saline solution on them.

Figure 3: Small Computer Numerical Control (CNC) machine with saline bath.

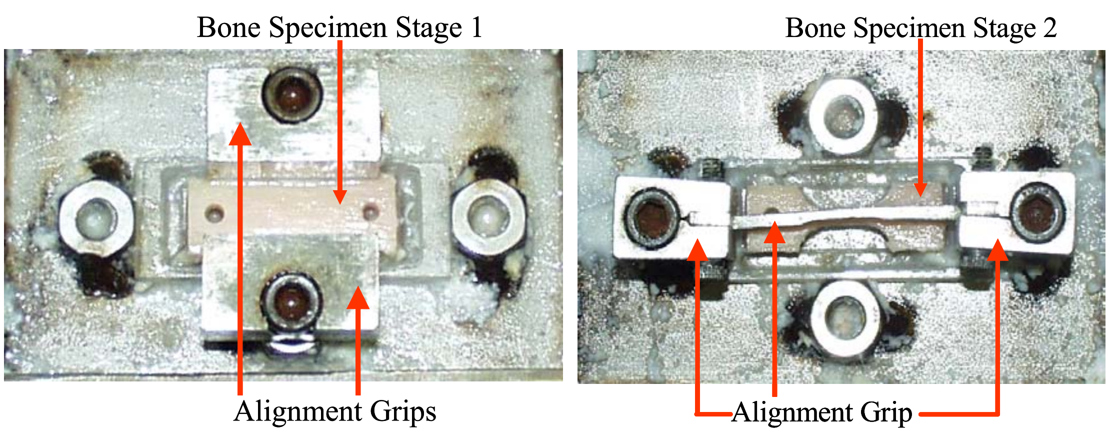

Figure 4: First set of grips secured specimen for the milling of the pin holes, top face, and ends (left). Second set of grips secured specimen for the milling of the dog-bone contour (right).

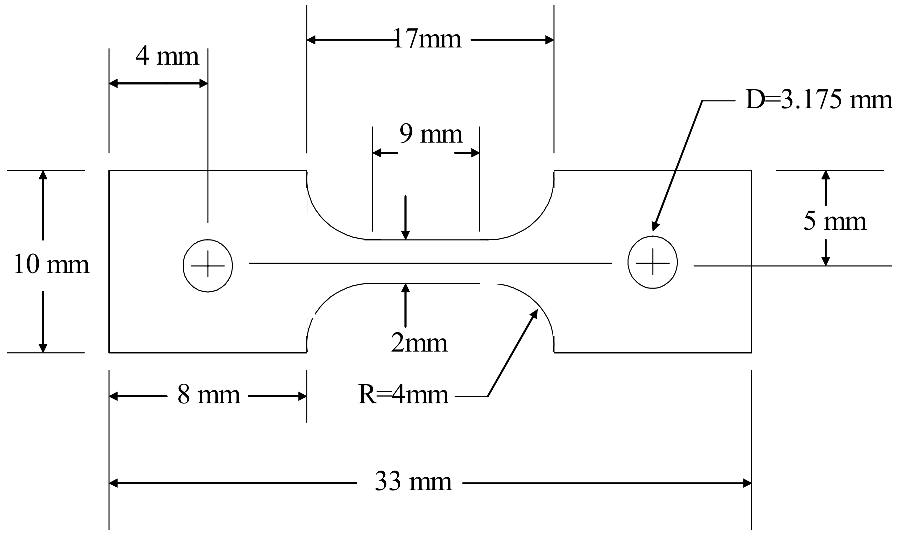

Figure 5: Axial tension specimen dimensions.
Note: Specimen thickness = 2mm.

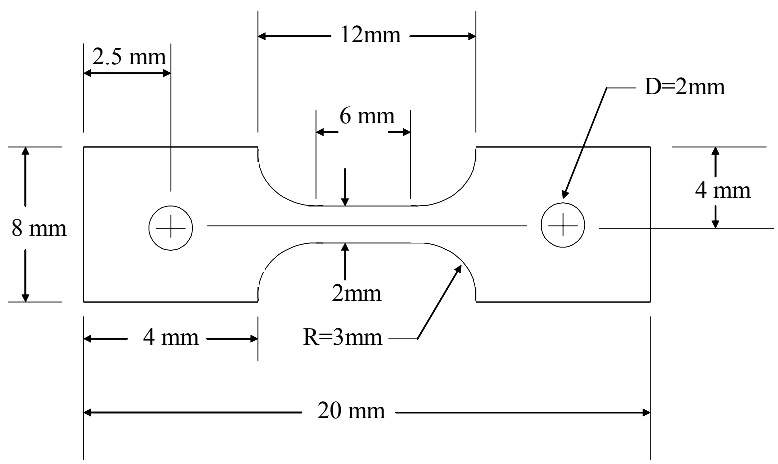

Figure 6: Lateral tension specimen dimensions.
Note: Specimen thickness = 2mm.

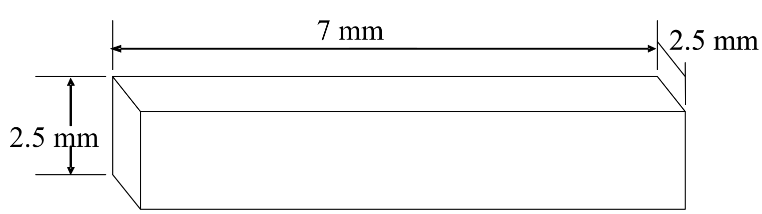

Figure 7: Lateral and axial compression specimen dimensions.

Alignment of Test Setup

Small misalignments of the material testing setup can result in variable bending stresses. Excessive bending can have noticeable effects on test results, usually seen as a reduction in both strength and ductility. There are three main sources of misalignment to address in tension and compression material testing: asymmetric machining of the test specimen itself, poor conformance of specimen centerline to top and bottom grip centerlines, or misalignment of top and bottom grip centerlines.

All three of these misalignment sources were addressed in this study. First, as described earlier, extreme care was taken during the specimen preparation process to maintain symmetric machining along the axis of interest of the test specimens. Second, the conformance of the specimen and grip centerlines was addressed through design and precise machining of the grips. For tension testing, the grips were designed to use both a pin and clamp configuration. The pin ensured proper centerline conformance, and the clamp provided the holding force (Figure 8). For compression testing, proper centerline conformance was ensured by milling a 1 mm deep circular placement groove, concentric with the grip centerline, in the top and bottom loading surfaces (Figure 9). The diameter of the placement hole was such that the corners of the compression specimen just slightly cleared. In compression testing, it is critical that the two loading faces are parallel. In order to compensate for any angular misalignment of the compression grips or faces of the compression specimen, lubricated rotating hemispheres were placed on the top and bottom grips (ASTM Standard E 9-89a). The compliance of the lubricant was taken into account by conducting a series of compression tests with no specimen in the grips. The resulting force versus displacement curves were then fitted and used to adjust the displacement data from the actual cortical bone compression tests.

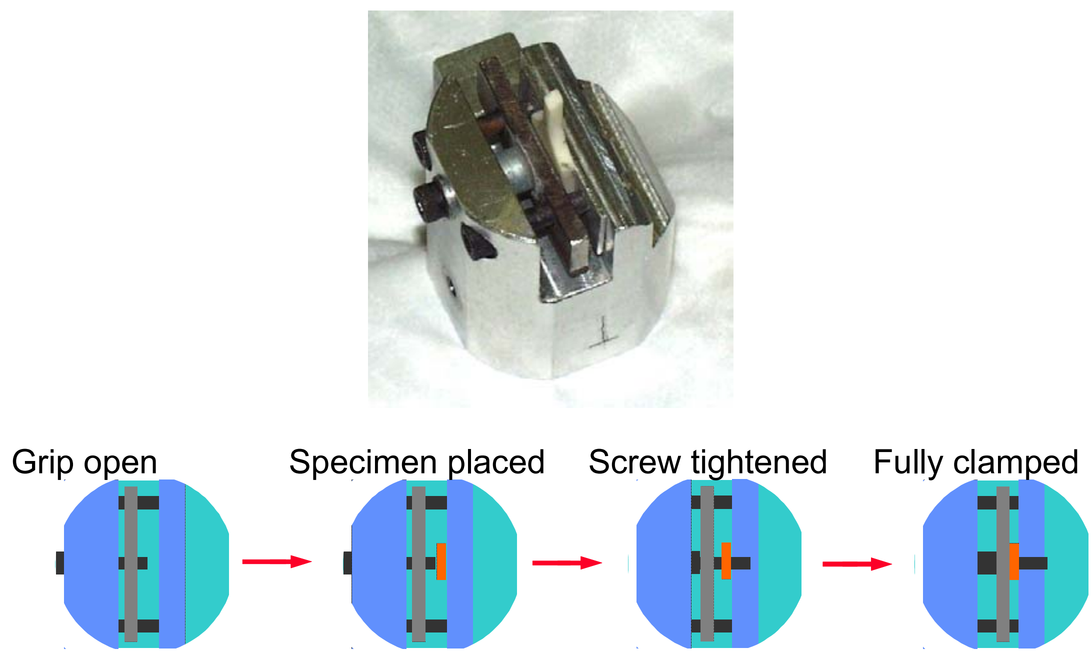

Figure 8: Tension test grips with pin and clamp design, where the pin ensured proper centerline conformance and the clamp provided holding force.

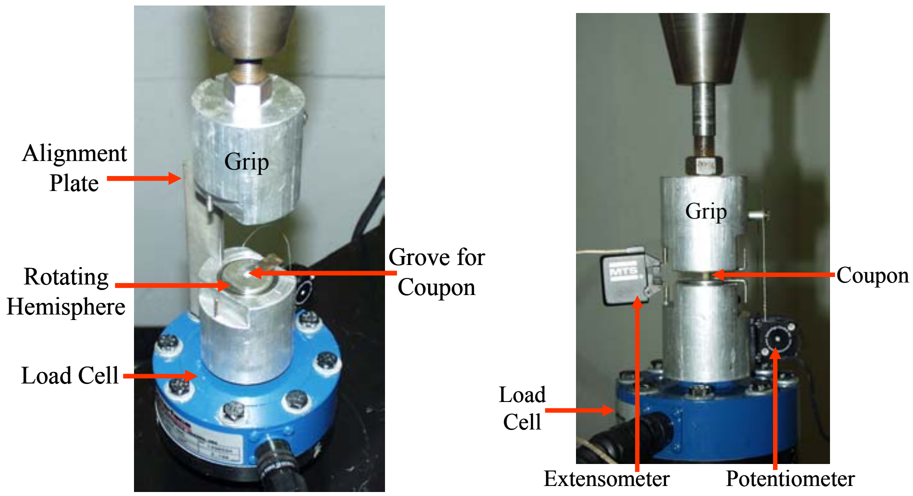

Figure 9: Compression test grips with centering groove to ensure proper centerline conformance.

In order to align the centerlines of the top and bottom grips, an aluminum specimen with the same dimensions of the cortical bone coupon was instrumented with strain gages on all four sides of the gage length (ASTM Standard E 1012-99). A dial indicator read the position so the load cell could be adjusted in small increments until the strain gages read within 100 microstrain of each other, which corresponded to 2-7 % bending (Figure 10). This procedure was conducted for both tension and compression grips.

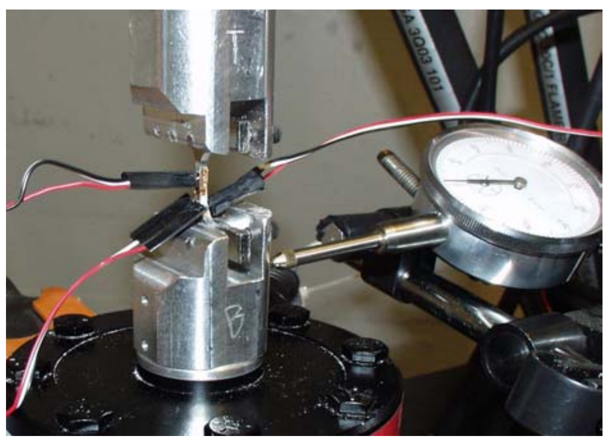

Figure 10: Tension grip alignment with use of strain gages.

MTS and Slack Adapter

A high-rate servo-hydraulic Material Testing System (MTS) was used to apply tension and compression loads to failure. For dynamic testing, the MTS actuator needs to travel a certain distance to reach the desired test speed. If the actuator is directly coupled to the test coupon, then a toe region will be seen in the stress vs. strain response. In order to avoid this, the use of a custom slack adapter was employed. A shaft with a male conical end rested inside a hollow tube with a female conical end, which was directly coupled to the MTS actuator. The MTS was programmed to lift or lower the slack adapter tube, depending on the testing direction, to allow enough space to reach the desired speed before coming into contact with the slack adapter rod. Once the MTS reached the desired speed and engaged the slack adapter, the piece was loaded at a constant rate to failure. The slack adapter was designed to work in both tension and compression test configurations (Figures 11 and 12).

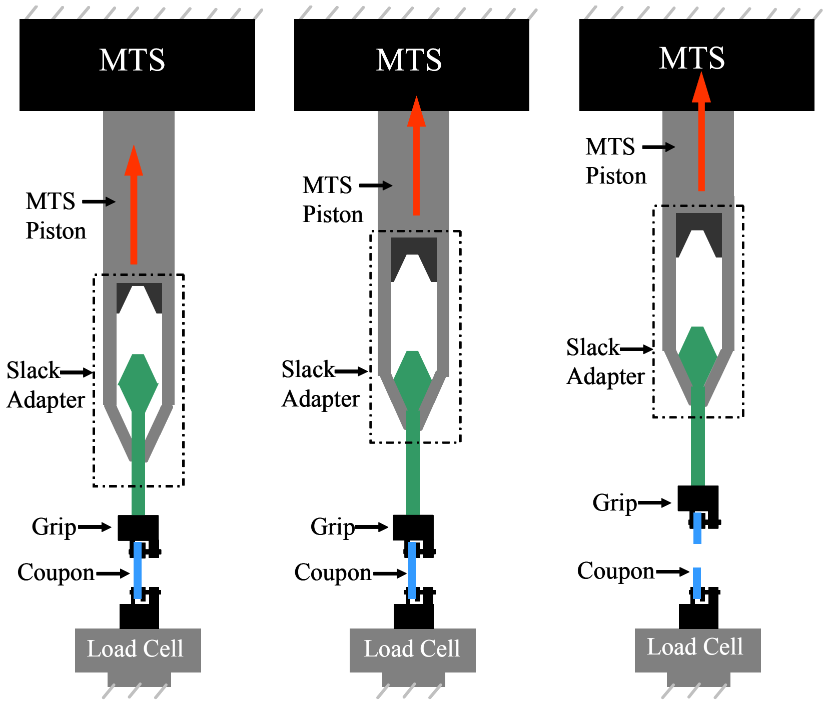

Figure 11: Slack adapter in tension test configuration.

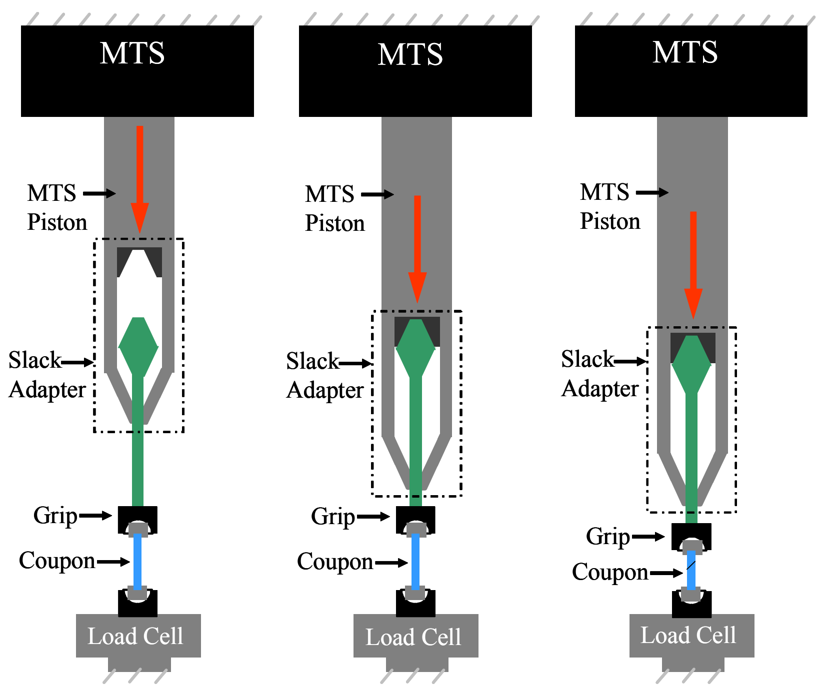

Figure 12: Slack adapter in compression test configuration.

Evaluation of Displacement Measurement Devices

A cortical bone tensile specimen with a 10 mm gage length tested at 5 strains/s will fail at 1-2% strain, or 100 to 200 microstrain, in about 3 ms to 5 ms. Therefore, a displacement measurement devise must have both high resolution and a high frequency response to be used in dynamic material testing of cortical bone. A total of five displacement measurement devices were evaluated for accuracy under both static and dynamic loading conditions. The devices included: a strain gage, potentiometer, extensometer, laser vibrometer, and the MTS internal LVDT (Figure 13). The strain gage and extensometer provided direct displacement measurements at the specimen gage length. The potentiometer, MTS internal LVDT, and laser vibrometer did not; therefore, these devices were calibrated using the data from the extensometer on the multiple static and quasi static tests. For the laser vibrometer, a triangular piece of metal, with reflective tape placed on it, was mounted to the top grip in order to reflect the laser back to the laser head.

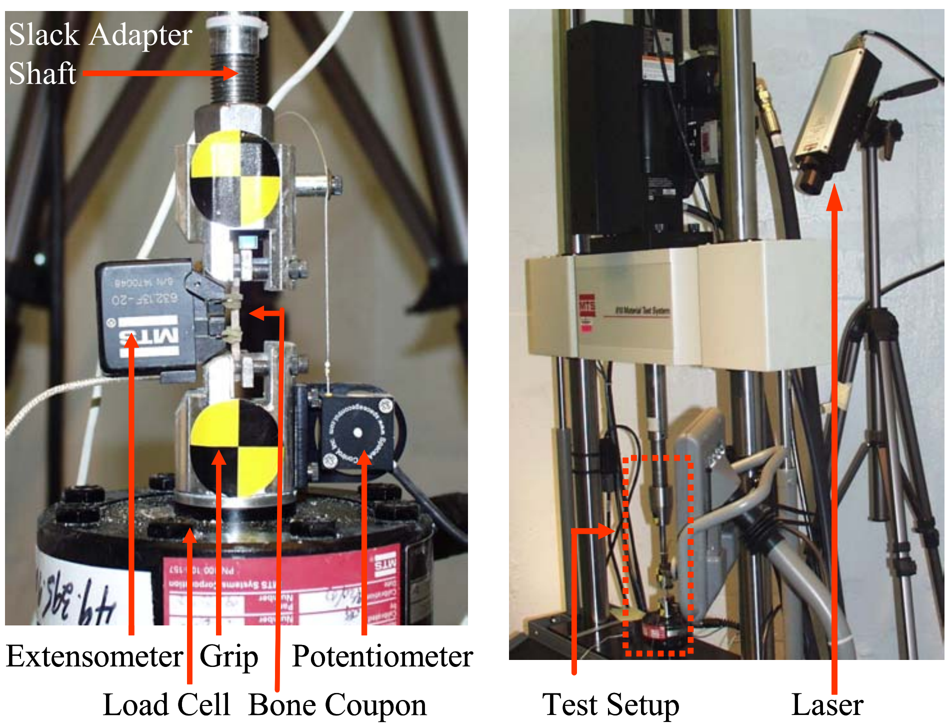

Figure 13: Evaluation of five displacement measurement devices
(Strain gage and LVDT not shown).

The standard displacement measurement device for static material testing is an extensometer. The extensometer provides a direct displacement measurement of the specimen gage length. However, the grips of the extensometer slip during the high rate tests resulting in inaccurate displacement readings. Like the extensometer, a strain gage provides a direct displacement measurement of the specimen gage length. However, tests conducted with a strain gage applied over the specimen gage length showed a large reduction in ultimate stress and strain. This was due to localized specimen drying, required to apply the strain gage, which has been shown to significantly affect the material properties, specifically plasticity, of cortical bone (Burstien, 1972). The potentiometer is a non-contact displacement measurement device, which does not affect the properties of the material being tested. However, the potentiometer data did not show the same response time as the extensometer for slow rate tests. The MTS internal LVDT was found to have relatively poor resolution. Finally, the laser vibrometer, which has nanometer scale accuracy and a high frequency response of 200 kHz, showed almost the exact response as the extensometer at static and quasi-static rates. Unlike the extensometer, however, the laser vibrometer also gives accurate readings during high rate testing (Figure 14).

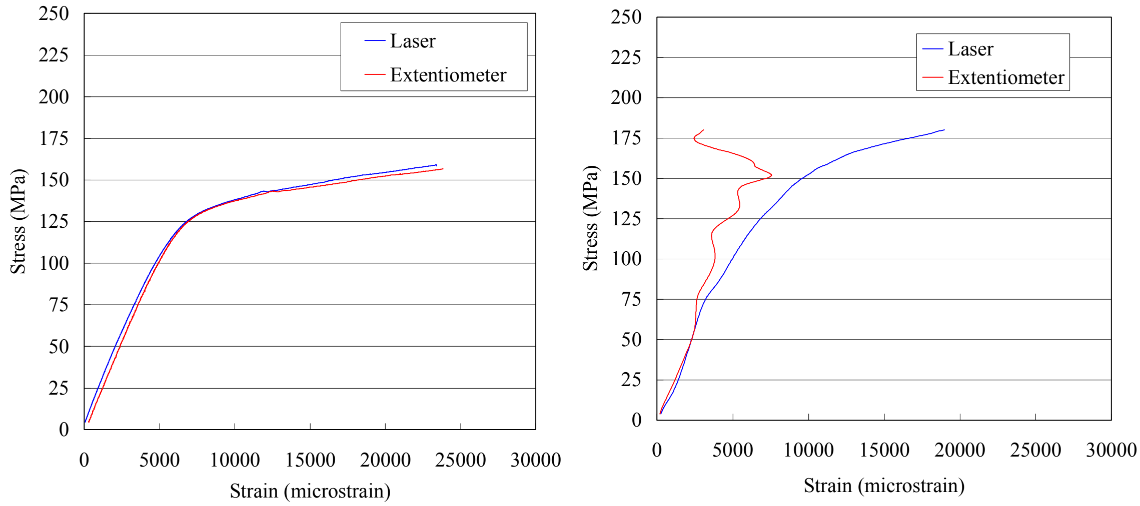

Figure 14: Tibia cortical bone tension stress vs. strain response at 0.05 strains/s (left) and 5.0 strains/s (right) using the both extensometer and laser vibrometer simultaneously.

RESULTS

The methods for dynamic material testing of human cortical bone presented in this paper, developed through 195 practice tests on human tibia cortical bone, proved to be both accurate and precise for determining cortical bone material properties. The average ultimate stress and strain of axial human tibia cortical bone loading at 0.05 strains/s were 150 MPa and 2.37% strain in tension, and 177 MPa and 1.61% strain in compression. The average ultimate stress and strain of axial human tibia cortical bone loading at 0.5 strains/s were 160 MPa and 1.92% strain in tension, and 208 MPa and 1.95% strain in compression. The average ultimate stress and strain of axial human tibia cortical bone loading at 5.0 strains/s were 165 MPa and 1.88% strain in tension, and 214 MPa and 2.11% strain in compression. A stress vs. strain curve for each tension testing speed is shown (Figure 15).

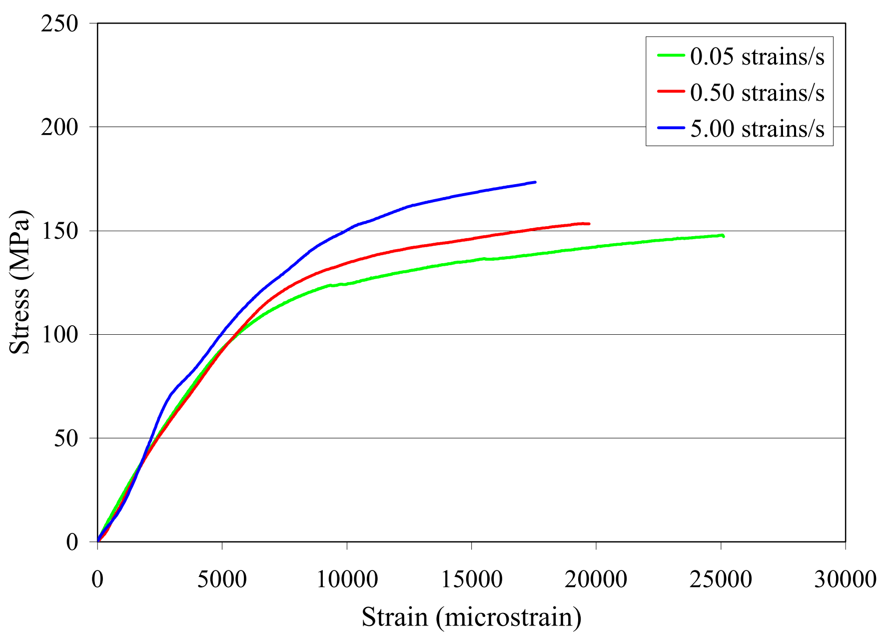

Figure 15: Tibia cortical bone tension stress vs. strain response at 0.05 strains/s, 0.50 strains/s, and 5.0 strains/s using the laser vibrometer.

CONCLUSIONS

In conclusion, a detailed methodology was developed for preparing and testing human cortical bone in tension and compression at dynamic rates to obtain accurate, comprehensive material properties. The key points of this methodology include: precise specimen preparation techniques to ensure the specimen remains properly aligned, hydrated and cool; proper alignment of the test setup and specimen to minimize the negative affects of bending; and use of a slack adapter to provide constant strain rates. A laser vibrometer, which has nanometer scale accuracy and a high frequency response of 200 kHz, was found to be the most accurate displacement measurement device at dynamic rates.

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DISCUSSION

PAPER: **Methods for Dynamic Material Testing of Human Cortical Bone Specimens**

PRESENTER: ***Andrew Kemper, Virginia Tech – Wake Forest Center for Injury Biomechanics and Toyota Motor Corporation***

QUESTION: *Guy Nusholtz, DaimlerChrysler*
Did you consider any of the shock wave effects when you knocked that thing down?

ANSWER: Like the stress waves?

Q: Well, stress waves, but you got other types of waves and you have geometric effects, which are going to occur as a result of the shocking.

A: We did—As you can see on the one test, you do see a little bit of a shock on the fast test. There's a wave, but we didn't do any kind of parametric study to find, like, the optimal specimen design to minimize that.

Q: Because if you look at—You look at the curve that you got presented, you see not that much of a difference between .05 and .5, but you see a big difference when you go up to 5. And typically, you don't see that type of difference, plus a shape change, in the manner that you're seeing.

A: Well—

Q: Do you think those are real? The first question is: Do you think those are real or could they be experimental artifacts?

A: Well, there is a chance that it's experimental artifacts, but if you see, the trend is going up and you're probably basing what you're saying on previous research that was done in the 60's or 70's where their data acquisition and their instrumentation wasn't quite as high as what we have now. So, there is some trend fitting that goes on there.

Q: Well, what I'm basing it on is general materials. When you look at strain rates, normally unless you've got some structural aspects, which is entering in or you're close to some transition point in material properties, you generally don't get that level of difference. So just based on a bunch of materials—plastics and different materials and compositions, you generally don't see that level of difference. It could be real. But because it's different from the general trend, it needs a bit more work to understand whether it really is or not.

A: I agree.

Q: Okay. Thank you.

QUESTION: *Andre Loyd, Duke University*
I had a question about your slack adaptor. Can you explain it one more time?

ANSWER: Sure. Okay. Basically in green here, you see, is just the rod that kind of sits inside of a hollow tube, and you have conical sections that mate on the bottom of the rod and on the hollow tube. As you can see, this can work in tension or compression. But basically, the rod is floating inside the tube at the beginning of the test. So the MTS and everything we have are actually mounted above the base plate. So, the entire hollow tube is moving relative to the rod until it reaches speed and then loads at the conclusion of the test.

Q: What were the rates of the MTS machine?

A: Well actually, I believe they were something on the order of .01 meter/second, .1 meters/second, 1 meter/second.

Q: Okay. Did you have any problems with vibrations?

A: No, we didn't really see very many problems with vibration. You're talking about, like, the impact of the socket after? No.

QUESTION: *Jason Kerrigan, University of Virginia*
Two questions for you actually. The very last slide that you showed where you compared some of the results… The very first line there, I think you had 133. Yeah. So, those are the ultimate strains ?

ANSWER: Yeah, ultimate strains.

Q: Ultimate strain, ultimate stress. Did you take a look at the slope of these curves at all in comparison with previous literature? Modules?

A: Yeah. They're comparable.

Q: And, correlation is good also?

A: Well, we were testing tibia and Raleigh & Bernstein tested femur. Yeah, femur.

Q: And you don't have any reasons that you would think there'd be any difference between those two?

A: Between the two bones?

Q: Between femur specimens machined from—

A: Yeah, it's been shown that material properties vary throughout the body and within each bone.

Q: Would you model or something or--? Second question is: At the beginning, I think you said something like 70 specimens? Is that correct?

A: There are 72 specimens.

Q: So in the previous slide from this slide, you showed the three curves. Are you guys seeing good correlation between specimens or is that just three different tests?

A: This is just three different tests--

Q: This is just three different tests.

A: That we're showing. Right.

Q: But are you seeing good correlation between a lot of multiple specimens tested at those rates?

A: Yes. We did various bodies, as well, too. It wasn't just all tested from one body. So there is some difference between each cadaver and within reason, we tried to stay within the mid-diaphysis of the bone, but you see some variation.

Q: Some variation of course between

A: But it's still fairly close to each other.

Q: Well excellent. Thank you very much.

A: Thank you.

COMMENT: *John Melvin, Tandelta*
Just a point of information. You talked about sampling rates and things of that sort. When Jack Wood did his work at Michigan, we used a device that probably most of the digital people don't understand anymore, but it's called the cathode ray oscilloscope and it did have the proper frequency response to make those measurements. So, it's a sampling problem there.

ANSWER: Okay. Thanks.

QUESTION: *King Yang, Wayne State University*
Your desire is to do a constant strain rate test, but by my own eyes—when looking at that video, it doesn't look so constant. Do you ever kind of plot your strain rate time history and check it out?

ANSWER: We did. What we're more interested in—We want a constant strain rate to reach the last region, but it's more like just a constant rate of the system. If you just start off without the slack adaptor, you'll get a toe region at the beginning of the test as the MTS concept is speed. So you kind of—We wanted to instantaneously load at speed; like, there are some small changes in the modulus through the strain rate at the beginning of the test.

Q: If you could show the video again, it looks like there is some jerking motion that makes me feel that it's not constant.

A: I think that's what Guy Nusholtz was saying that there is some vibration or some waves propagating through that might need further investigation.

Q: Okay. Now just rephrase my question is: How constant is this constant strain rate?

A: Well for the, upwards—For the lower rates, it is fairly constant; but as we get up to uphill, we do have problems. There might be some problems with the, you know, stress waves and the property of getting through. It was the best that we could do with the system.

QUESTION: *Eric Meyer, Michigan State University*
My question is: During your preparation of the CNC millimeter machine, you kept it hydrated?

ANSWER: Yes.

Q: So this was at room temperature?

A: Approximately room temperature.

Q: Okay. And during testing, was it hydrated at room temperature?

A: Yes. While the specimens were waiting to be tested, they were kept emerged in saline. And then when we were getting ready to test, they were kept hydrated by spraying saline on them, making sure that they didn't dry out, and we tested them fairly quickly after we removed them from the saline bath.

Q: So during testing, they weren't being hydrated, like in a bath or something?

A: No. They weren't immersed in anything during testing.

Q: And my other question is: Your stress/strain curves—Is that engineering stress and strain? Did you see any plastic-type deformation going on or is that all elastic up until--?

A: We see the plastic region test past the yield point. Is that what you mean?

Q: So I mean, I just wondered if you included or looked at that as far as your specimens. Like, were you trying to investigate the plastic region at all?

A: Yes. We're looking at the plastic region and we want to see how much it strains, and we did see a little bit more strain than some previous research has seen: Between our set of our specimen preparation, our alignment techniques. Yeah, we're seeing a good deal of –

Q: Yeah. I just thought there's a correlation between preparation method and how much plastic strain you might see.

A: That's only—I mean if you don't keep the specimen wet, it becomes much more brittle and it can significantly reduce the plastic.