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Bending and torsional stiffness measurements of equine radii and tibiae

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Summary: This study was a re-evaluation of static mechanical testing of equine long bones as part of a larger study on impact failure modes and strength of the same bones. Supplementary to other morphological and mechanical tests, static stiffness properties of these long bones were non-destructively determined. The goal was to quantify stiffness properties of the diaphysis of equine radii and tibiae in quasi-static bending as well as when loaded in torsion and to check for possible age and gender effects on these properties. Fifty-six equine bones (tibiae and radii) from fifteen horses were first tested in a torsion machine and subsequently fifty-five of them investigated using a 3-point-bending test-setup. A maximum torque of 150 N*m and a maximum bending moment of 920 N*m were applied in steps. Loading and unloading was performed in order to check for hysteresis effects. The outcome for both type of bones (tibiae and radii) was described statistically in relation to age (young, middle aged, and old) and gender (geldings and mares). Additional information on the side (left and right), breed and use of the horse (competition versus 'other', such as pleasure) was excluded from statistical modelling after preliminary analysis. While the loading-unloading cycles in bending showed some hysteresis due to localized deformation, the unloading curve followed the loading curve in torsional loading. Bending stiffness of tibiae is on average 6'813 N/mm and of radii 6'130 N/mm. Torsional stiffness of tibiae is 2.36*10^6 N*m(rad/mm), and of radii 1.90*10^6 N*m(rad/mm). Tibiae were clearly stiffer than radii. A trend of higher bone stiffness for geldings compared with mares and for younger horses could be found, although not statistically significant.

Keywords: bones / horses / bending / torsion / stiffness / orthopedics

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Introduction

In animals and humans long bones primarily have to be stiff, i.e. they have to function without deforming much under load (*Currey* 1981). The bone strength is also of great but secondary importance. Both the stiffness of a bone and its strength depend on two factors: (1) the stiffness and strength of the bone material itself, i.e. the bone material properties and (2) the architectural properties of the whole bone (*Currey* 1999 and 2006, *Reilly* and *Burstein* 1974, *Reilly* and *Burstein* 1975). A large number of studies have been performed to characterize material properties of cortical or cancellous bone tissue, such as density, bone mineral content, hardness, elasticity (stiffness) and strength; for an overview see for example (*Guo* 2001). Bone architectural properties, e.g. length, thickness of cortical bone, cross sectional area, and resulting parameters such as moment of inertia, have also been studied (*Currey* 2001).

The bone can be loaded in bending in order to determine the bending stiffness, i.e. the ratio between the applied load and the resulting deformation. Standard three-point bending tests have been performed on equine bones, such as the metacarpus (*Schryver* 1978, *Lawrence* et al. 1994). *Hanson* et al. (1995) have performed bending tests with different segments of the diaphysis taken from various equine bones. Bending stiffness was approx. 5'200 N/mm for both tibiae and radii. They also performed torsional testing. Torsional stiffness was approx. 1'200 N*m/rad.

In the case of a horse, the bones in the legs are loaded primarily in compression and bending. For other types and directions of loading the bone may be weak (*Currey* 1968). Nevertheless, the loads during galloping or jumping are still a factor of 3 lower than the ultimate strength of the bone (*Biewener* et al. 1983). This reserve factor of 3 is typical also for other animals. During landing, compression stresses up to 80 MPa can be reached, whereas this bone breaks at approx. 200 MPa. The loading of the bones during walking is approx. 2.5 times the body weight, whereas during trotting the loading can be up to 5 times the body weight. The ultimate compression stress during trotting is around 45 MPa, but fracture strength is beyond 85 MPa (*Piotrowski* 1983).

The loading on a bone during locomotion or athletic activities can be divided into compression or tension, bending, and torsion. For example, Schneider et al. have shown that radii and tibiae of horses experience not only compression, but also significant bending and torsion under natural living conditions (*Schneider* et al. 1982). Curry and others have pointed out that a bone under axial loading can be subject to Euler buckling (*Currey* 2001). This failure type is especially important if the shape of the bone is not exactly symmetrical. This is in practice always the case. Hanson et al. have measured the geometry of various equine long bones, including radii and tibiae (*Hanson* et al. 1994). They have shown that there rarely exists a significant difference between left and right leg bones. In another study the same authors reported structural properties from the same group of bones (*Hanson* et al. 1995). They performed 4-point bending, torsion and compression tests on specimens cut from the diaphyseal part of the cortex. Bending, torsional and compressive stiffness values were determined. All bones showed the same stiffness, with the exception of bending stiffness. In bending, tibiae were more than 50% stiffer than radii. Ultimate failure bending moments were also determined. Large differences (up to a factor of 4) were reported in elastic moduli measured from whole bones and from cortical specimens.

The primary aim of this study was to quantify the stiffness properties of equine tibiae and radii in bending and in torsion. We measured the diaphyseal stiffness properties in bending and torsion by non-destructive testing. The secondary aim was to clarify if bone stiffness is influenced by the age or gender of the animal. While a reduction of bone strength and stiffness with age is well known in human bones, such an effect has not yet been studied for equine bones.

Material and methods

Material selection, preparation and pre-test examination

Between 2001 and 2004 a total of 56 bones (radii and tibiae, left and right side) were collected from fifteen euthanized horses. The horses were aged between 4 and 21 years and had been euthanized for various reasons such as colic and behavioural problems (see table 1). None of the horses suffered from a bone disorder. The horses were mainly warmbloods (11 of 15). Nine horses were geldings, and six were mares. One bone (the right radius of animal No. II), could not be tested in bending due to a manipulation error during the torsional test. Three bones (right tibia and right radius from animal No. X and the left radius from animal No. XIV) were used in pre-tests for another study and were not available.

Immediately after euthanasia, the bones were stripped of soft tissue and wrapped in a cloth soaked in 0.9% physiological saline solution. They were stored in a closed plastic bag at -20°C until further processing. Two weeks before the start of the investigation, the bones were thawed and prepared. Any remaining tissue such as muscle, tendons, ligaments and attachments of articular capsules was removed. Any ulna or fibula which extended beyond the proximal end of the radius or tibia was sawed off. The length of the bone was measured with a sliding calliper and the geometric centre was determined. The bones were between 36.4 cm and 42.5 cm long. Some of the bones had to be shortened to 38 cm so that they fit the testing rig. This was equivalent to a shortening of not more than approx. 10% of the total length. The bones were shortened by equal amounts at the proximal and distal epiphysis.

The next step was to cast both ends of each bone in polyurethane (Biresin G26/G28 from Sika AG, Bad Urach, Germany), such that the widest part of the epiphysis was embedded, see Fig. 1. Prior to the static tests, the bones were examined macroscopically and by X-ray. The purpose of these pre-test examinations was to ensure that the bones had not suffered prior damage. The bones were again wrapped in cloths soaked in saline solution, packed in plastic bags and stored at 4°C until the tests started. The bones were warmed up for 12 hours before testing at room temperature (24°C), but still within their wrapping. The plastic bag and the cloths were removed only during testing (for less than 15 minutes). All static tests were carried out at room temperature.

Fig. 1 Typical specimen after preparation

Table 1 Gender, age, breed, use and reason for euthanasia of 15 horses used for stiffness measurements of the radius and the tibia

Animal No.	Gender	Age [years]	Breed	Use	Reason for euthanasia
I	Gelding	20	Swiss warmblood	Pleasure	Cardiac disease
II	Gelding	14	Hungarian warmblood	Competition	Kissing spines
III	Mare	10	Irish warmblood	Competition	Back problem
IV	Gelding	21	Thoroughbred	Pleasure	Ruptured ligament
V	Gelding	17	Swiss warmblood	Pleasure	Trauma
VI	Mare	4	Swiss warmblood	Pleasure	Epiglottic entrapment
VII	Mare	11	Swiss warmblood	Pleasure	Sarcoids
VIII	Gelding	9	Hanoverian warmblood	Competition	Hoof abscess
IX	Mare	10	Wuerttemberg warmblood	Pleasure	Behavioral problem
X	Gelding	15	Dutch warmblood	Pleasure	Colic
XI	Mare	7	Thoroughbred	Pleasure	Melanoma
XII	Gelding	18	Dutch warmblood	Pleasure	Colic
XIII	Gelding	11	Franches-Montagnes	Pleasure	Colic
XIV	Mare	14	Franches-Montagnes	Blood mare	Intoxication
XV	Gelding	15	Swiss warmblood	Pleasure	Ruptured tendon

Bending

The bending test rig was a custom-built device (Fig. 2). It was similar to the one used by Nyquist for human long bones (*Nyquist* et al. 1985). The set-up consisted of a rigid frame which had support pins set 23 cm apart. The bone was laid upon the support pin without any fixture on the lateral side but constrained in torsion. The load was introduced in the centre of the span width in medio-lateral direction by a cylindrical steel pin (diameter = 7 mm) oriented perpendicularly to the bone axis. This orientation was chosen because the impact tests (*Piskoty* et al. 2012) were planned to direct the impact load in this sense. The load was applied in steps of 1'000 N up to a total load of 4'000 N, followed by unloading back to zero with the same step width. The loading rate within each step was approximately 33 N/sec. Each loading step was held for 2 minutes in order to measure the deformation in a stabilized condition, e. g. to take possible time-dependent effects into account. This measurement methods followed common practice (*Pelker* et al. 1984). The displacement of the pin relative to the support structure was measured with a mechanical device (METRA Type 0.01 mm/div from Metra, Renens, Switzerland). The deformation of the bone between the supports and the mid-section was measured optically with help of a video extensometer (M46 from Messphysik GmbH, Fürstenfeld, Austria). This 3-point-bending setup was tested with specimens made of wood and calibrated with an aluminium tube. The measured bending stiffness of this reference tube would be measured with an accuracy of 5%. The mean values of these deformations (obtained during the hold time periods) were recorded for further analysis.

Torsion

Torsional stiffness was measured with help of a torsion test machine (Tinius Olsen 5884 Nm from Tinius Olsen, Horsham, Pennsylvania, USA) with a custom-made optical twist measurement system (Fig. 3) according to standard principles, see *Turner* and *Burr* 2001. Torque was generated with help of a 5 kg weight applied off-centre to the bone axis leading to a distal torque in the bone. A maximum torque of 150 N*m was introduced. The load was applied in 3 steps of 50 N*m up to a total load of 150 N*m, followed by unloading until zero with

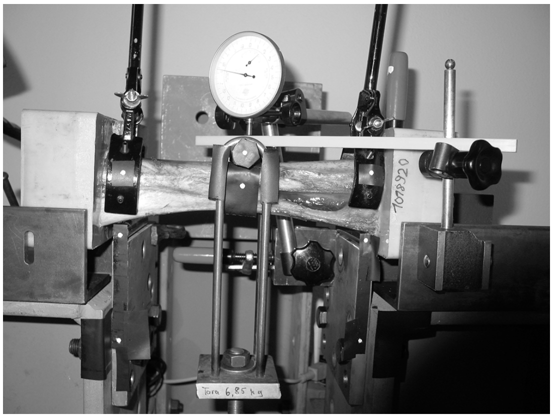

Fig. 2 Bending test set-up

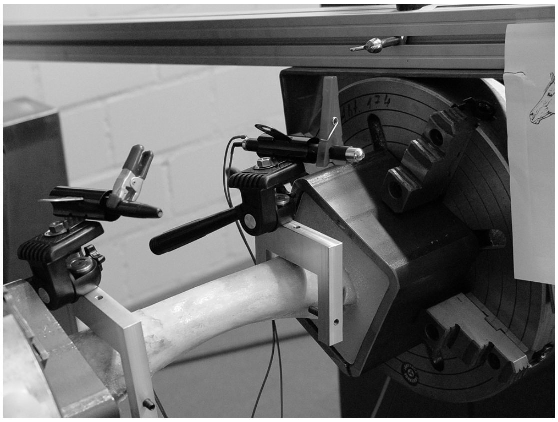

Fig. 3 Torsion test set-up

Table 2 Stiffness properties of tibiae and radii

		Tibiae		*Radii*		
	Subgroup	*Mean*	*Stand. deviation*	*Mean*	*Stand. deviation*	*Animals n*
Bending stiffness tibiae [N/mm]	*Geldings*	*6896*	*1003*	*6424*	*1223*	*9*
	Young geldings					*0*
	Middle aged geldings	*6919*	*679*	*7062*	*1278*	*5*
	Old geldings	*6868*	*1437*	*5626*	*529*	*4*
	Mares	*6687*	*1211*	*5689*	*606*	*6*
	Young mares	*7983*	*579*	*6259*	*201*	*2*
	Middle aged mares	*6039*	*809*	*5404*	*523*	*4*
	Old mares					*0*
*Torsional stiffness tibiae [N*m/(rad/mm)]*	*Geldings*	*2.49*	*0.49*	*2.02*	*0.36*	*9*
	Young geldings					*0*
	Middle aged geldings	*2.63*	*0.57*	*2.15*	*0.41*	*5*
	Old geldings	*2.32*	*0.34*	*1.86*	*0.25*	*4*
	Mares	*2.17*	*0.35*	*1.71*	*0.32*	*6*
	Young mares	*2.34*	*0.12*	*1.89*	*0.38*	*2*
	Middle aged mares	*2.09*	*0.41*	*1.63*	*0.30*	*4*
	Old mares					*0*

the same step width and reloading up to 150 N*m again. The loading rate within each step was approximately 16 N*m/sec. Each loading step was held for 2 minutes. Torque was measured mechanically by the machine at one end of the fixture. The twist of the bone was measured optically at the nominal distance of 21 cm by the projection of two beams generated by laser pointers (5 mW red laser pointer pen from Distrelec, Switzerland) on a wall 6 m away from the axis of torsion. The projected distances were recorded manually. For a meaningful comparison between bones, twist deformation was measured within 30 seconds after torque was applied (accuracy 1 %). Twist was calculated in rad/mm for each bone and correlated with the measured torque at each load step.

Statistical analysis

First we summarized all the stiffness data by descriptive statistics (table 2). The means and standard deviations of the bending and torsional stiffness values for tibiae and radii have been calculated separated with respect to gender and age. For this analysis age was classified in three groups (The sample had no old mares and no young geldings.):

- young horses: Age less than 9 years
- middle aged horses: Age between 9 and 16 years
- old horses: Age higher than 16 years.

Second we performed mixed effects regression analysis using the software R (http://www.r-project.org, Jan 2014). In a preliminary analysis the following variables were examined: Breed, use, age, gender and side. For the final regression analysis however we decided to omit breed, use and side for the following reasons: No meaningful classification of breed and use could be found and no practical outcome could be expected though. The difference between sides was in all cases by an order of magnitude smaller than the differences between the other variables. Therefor we concluded that it was reasonable to omit side as well. A logarithmic transformation was applied to both stiffness types to meet model assumptions of constant variance. To account for possible correlations between measurements of bones from the same horse, a random effect (additional source of variation) of horse (via the animal identification number) was included in both regressions. Age (centred and scaled), bone type (radius or tibia) and gender (gelding or mare) were included as fixed effects in both regressions. The result of the torsional stiffness measurement of the right tibia of animal No. 4 was a clear outliner, and was therefore excluded from the regression analysis of the log-torsional stiffness. We checked the row data, but could not find an obvious reason for that. We used a 5% significance level to report our results and applied Bonferroni corrections for the six tests that were applied (three tests per stiffness type). The best-fitting regression for both the log-bending stiffness and the log-torsional stiffness resulted in an additive effect of type of bone, age and gender.

Results

Determination of the stiffness values

Figure 4 depicts a typical load-displacement curve from the bending test. Bending stiffness was calculated from the average of the loading and unloading branches of the load-displacement curve (not including the measurements at zero load level) in order to account for hysteresis effects. The bending stiffness was defined as the ratio of the load applied centrally in medio-lateral direction, per unit deflection of the bone at this section. In contrast, torsional torque-twist curves did not exhibit any hysteresis effects (Fig. 5), hence torsional stiffness was computed as the slope of a single linear fit through all the data points of the torque-twist curve. Torsional stiffness was defined as the ratio of the torque applied in the longitudinal direction, per unit twist and per unit length of the bone.

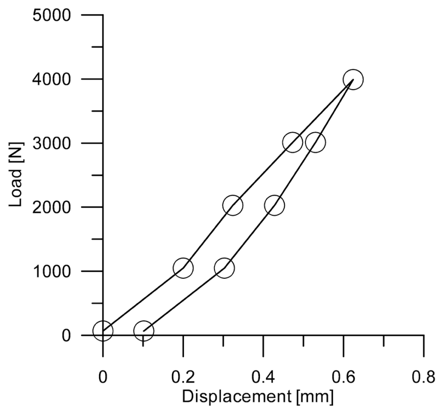

Fig. 4 Bending test: Typical load versus displacement curve

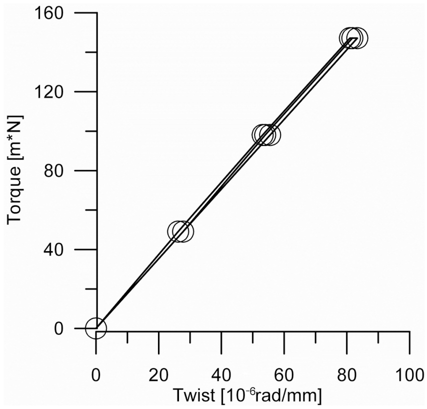

Fig. 5 Torsion test: Typical torque versus twist curve.

Table 3 Comparison between stiffness properties from geldings and mares

		Tibiae			Radii		
Tibiae	Animals n	Geldings	Mares	Difference [%]	Geldings	Mares	Difference [%]
Bending stiffness [N/mm]	9 / 6	6'896 ± 1'003	6'687 ± 1'211	3.1	6'424 ± 1'223	5'689 ± 606	12.1
Torsional stiffness [N*m/(rad/mm)]	9 / 6	2.49 ± 0.49 *10^6	2.17 ± 0.35 *10^6	13.7	2.02 ± 0.36 *10^6	1.71 ± 0.32 *10^6	16.5

Analysis of the stiffness data

From the descriptive statistics (table 2) and the graphical presentation (Fig. 6 to 9) we had the impression of an age and a gender effect on both stiffness values. The difference between mare and gelding were between 3.1% and 16.5%, see table 3. In order to check the statistical significance we studied the same data set with linear mixed effects regression modelling, s table 4. For the log-bending stiffness, the variation between horses in the linear mixed effects regression was considerable (a standard deviation of 545’904 N/mm), comparable to that of the residuals. A statistically significant effect for bone type (after Bonferroni correction) was detected, such that the tibiae have a larger bending stiffness than radii. Age was estimated to have a decreasing effect on the bending stiffness, and mares were estimated to be less stiff than geldings. But these effects were not statistically significant. It is important to remember that the lack of statistical power in this regression does not imply that there truly were no effects on age and gender on the bending stiffness of bones. Note that the standard errors are relatively large compared to the estimated effects; this is due to the small sample size available for estimation.

For the log-torsional stiffness, similar results were found. Bone type had a statistically significant effect: the torsional stiffness of radii was less than of tibiae. The variation due to horse was much larger than that of the residuals (0.382 N*m[rad/mm] versus 0.105 N*m[rad/mm]). Although not statistically significant, there was a negative trend for age, decreasing the torsional stiffness, and geldings were stiffer than mares.

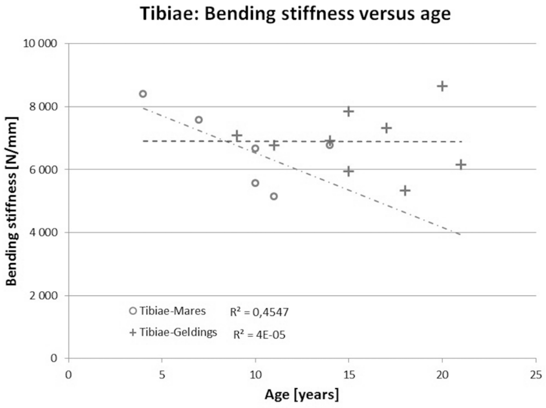

Fig. 6 Tibiae – Bending stiffness versus age

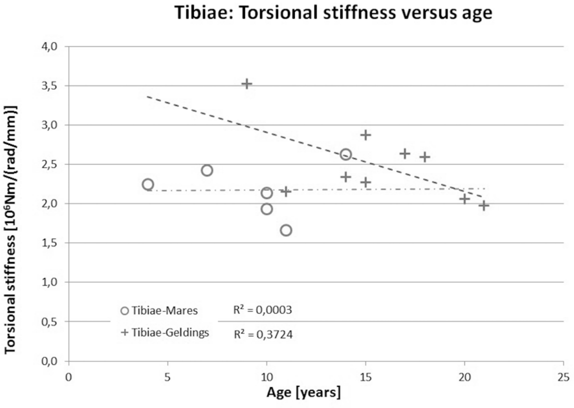

Fig. 8 Tibiae - Torsional stiffness versus age

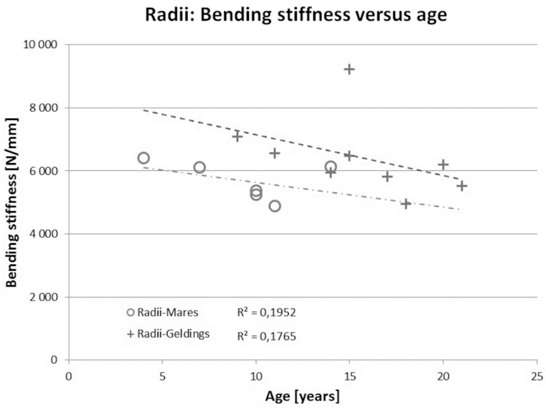

Fig. 7 Radii – Bending stiffness versus age

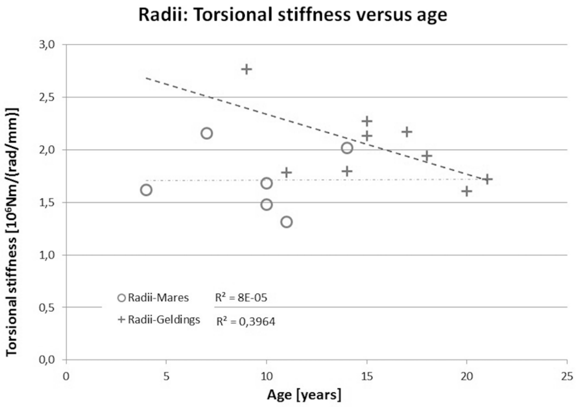

Fig. 9 Radii - Torsional stiffness versus age

Table 4 Results for linear mixed effects regressions for log-bending and log-torsional stiffness. Age was centred, and thus the intercept corresponds to the estimated mean stiffness of the radii of geldings at the mean age (12.3 years).

Variable	Log (Bending stiffness) [N/mm]					Log (Torsional stiffness) [*10⁶ N*m/(rad/mm)]				
	Estimated coefficient	Standard error	$e^{(Coef.)}$	LRT	$P(X^2)$	Estimated coefficient	Standard error	$e^{(Coef.)}$	LRT	$P(X^2)$
Intercept	8.7388	0.0348	6240.4			0.7122	0.0434	2.038		
Radius vs Tibia	-0.0609	0.0192	0.940	9.29	0.002	-0.1152	0.0057	0.891	99.45	0.000
Gelding vs Mare	0.0809	0.0456	1.080	3.51	0.061	0.1312	0.0570	1.140	5.48	0.019
Age	-0.0727	0.0459	0.930	2.85	0.091	-0.0841	0.0581	0.919	2.42	0.120
Residual std. dev.	0.1417					0.0416				
Animal std. dev.	0.1076					0.1617				

Discussion

Both load configurations were analysed in detail by *Wullschleger* et al. (2010). They compared experimentally found stiffness values with calculated values from a finite element modelling using various bone material models.

Because the deformation had a non-reversible part in all cases, the bone tested in the pre-test was examined carefully. Plastic as well as viscous deformations or damage to the bone structure could be possible causes of such a non-linearity, (*Nyquist* et al. 1985). However in our case, the maximum applied load was far lower than the estimated bending strength. Another reason could be the formation of indentations where the loads are applied to the bone, (*Turner* and *Burr* 1993). From the examinations it could be concluded that the permanent deformation was indeed caused by local indentations at the point of load application and was not due to overloading or plastic deformation in the rest of the bone. Therefore, the bending test was judged to be non-destructive in the main part of the bone. The testing scheme that was applied assured that strain rate effects would be insignificant, because the maximum strain rate in the specimen was in the order of 1×10^{-5} sec^{-1}. In the literature, strain rate effects on mechanical properties such as the elastic (relaxation) modulus in compact bone are reported to be within 10% for strain rates between 1.5×10^{-1} sec-1 and 1.5×10^{-4} sec^{-1}, (*Lakes* et al. 1979, *Fondrk* et al. 1988).

During the torsion test set-up, the load level was sustained without any indications of damage to the bone, such as acoustic sign or permanent deformation after unloading. Therefore this test was non-destructive in nature. In a pre-test we saw that twist introduced by a torque is time dependent: Twist deformation was altered by 0.03% per second (35% after 20 minutes) of hold time at maximum torque of 1'500 N*m. We decided to take the measurement after 1 minute of hold time.

Bending and torsional stiffness values of whole bones have been measured earlier. The mean value for the tibia for torsional stiffness can be compared to values found by McDuffee et al. (*McDuffee* et al. 1994 and 1997), but for bending we cannot directly compare the values, because the bone orientation was not the same (medio-lateral versus cranio-caudal) and the inter-support length was also different (23 cm instead of 32.5 cm). If we assume, by using classical beam theory, that the deformation is quadratically proportional to the inter-support length, we can estimate the bending stiffness over 23 cm. This stiffness would be doubled (32.5/23.0)2 =1.99). So we get a value of 2*2.34 kN/mm=4.67 kN/mm for the tibia measured by *McDuffee* et al. 1994. The value for bending stiffness from the study reported by the same author in 1997 are given in Nm/mm. Transformed to kN/mm the stiffness is very close to the value reported by *McDuffee* et al. in 1994 (2.31 kN/mm versus 2.34 kN/mm.) These values of both references are less than what we have measured for tibiae (6.81 kN/mm). This difference can be attributed to the different orientation of the bone.

As said, torsion stiffness values for tibia reported by *McDuffee* et al. (1994) can be directly compared to our results. They measured the torsional stiffness over the full length of 380 mm and found stiffness values of 84.15 N*m/°. This equals to $1.83 \cdot 10^6$ N*m/(rad/mm), which is 22.5% less than our values ($2.36 \cdot 10^6$ N*m/(rad/mm). This difference can be explained by the thicker cross section of the bones in the metaphysis and epiphysis compared to the diaphysis. In our case we measured the torsional stiffness only over the diaphysis, which is the slenderest part of the bone.

The symmetry of the data with respect to the horse body (left versus right) has been expected, because other studies on similar bones came to the same conclusion (*Hansen* et al., 1994 and 1995). If in future studies a side effect will be considered, we recommend to check for a possible "over-the-cross handedness". We had the impression that, such an effect could be present: Assuming that an animal is a left-hander, if its left radius is stronger than the right radius, its right tibia should then be stronger than its left tibia and vice-versa. Further experiments with larger sample sizes would be necessary to more accurately estimate such over-the-cross asymmetry effects in bone stiffness. The fact that the tibia is stronger than the radius is not surprising: although they look similar they are anatomically different, and from their location in the body (back leg versus front leg) they experience different load levels. Hanson et al. also found a significant difference between the two types of bones (*Hanson* et al. 1995).

In the literature, age and gender effects have been discussed on various properties of bones. For example, in the study done by *Burstein* et al. (1976), stiffness in bending and in torsion were found to be independent of age and show no significant variations with gender. On the other hand, those authors found significant variations with age in human femora but not in human tibiae. In the same study, they found a decreasing material strength and a decreasing Young's modulus with age. While a reduction of bone strength/stiffness in human bones is well known, such an effect is not very well documented for equine bones. We hypothesize here that stiffness of long bones is affected by two factors: Size of the bone and material stiffness. Probably the influence of size is more pronounced than the effect of material stiffness. Because geldings are in general larger than mares, we expect a gender effect on bones size. If so we should find bones from gelding being stiffer than bones from mares. The reason why we do not see this effect in both values (bending stiffness and torsional stiffness) may be caused by a different sensitivity of the bending stiffness and the torsional stiffness on the size of the bone. A second reason might be a difference in accuracy of its experimental determination. To clarify a gender effect on bone size, we plan to perform similar statistical analysis with the same set of bones with respect to various dimensions. This will be based on size measurements performed during the Xtreme computed tomographic study (*Fürst* et al. 2008a), where not only mineral density and bone micro-architecture were measured for each bone, but also the (diaphyseal and metaphyseal) diameters, perimeters, and cross sectional areas, as well as second and polar moments of inertia. Primarily we will have a closer look at moments of inertia, because following classical beam theory, bending stiffness is proportional to the second moment of inertia and torsional stiffness is proportional to the polar moment of inertia.

Interestingly the study (*Fürst* at al. 2008a) has shown that mineral density and bone micro-architecture (*Fürst* et al. 2008a) show an age effect but no gender effect. Our interpretation of the stiffness data so far is that two effects are overlapping: First material stiffness is decreasing with age and second gender makes a difference in bone stiffness via its size. This interpretation is supported by the results from bone material measurements: Stiffness is linearly dependent on Young's modulus, and Young's modulus is correlated with bone material micro-architecture. Therefore a reduction of bone stiffness with age can be expected with the weakening of the bone material with age. In conclusion we hypothesize here, that while bone material properties are not affected by gender (see conclusions by *Fürst* et al. 2008a), the size of the bones can be: Bones from geldings are probably larger than bones from mares. A gender effect on bone stiffness would be explainable by a gender related size effect on the bones. Such a size effect was already mentioned by *Fürst* et al. 2008a: The slice area and the thickness of the cortical bone are larger for tibia compared to radius as well as for geldings compared to mares.

Each of our bones were fractured afterwards in a side impact test, see (*Fürst* et al. 2008b, *Piskoty* et al. 2012) and the two static properties could be used as characteristic strength values of these individual bones. During the evaluation phase of the whole program we tried to find cross-correlations between the various properties of the bones. However the statistical basis of the samples was not large enough to allow further conclusions with statistical evidence.

Conclusions and outlook

The main goal of this study was to determine the stiffness of each individual long bone in the two load cases bending and torsion. A significant difference in both torsional and bending stiffness can be seen between tibiae and radii. Tibiae are stronger than radii. In addition, some evidence that bones from geldings are stiffer than bones from mares and bone stiffness decreases with age was observed. For a confirmation with statistical evidence of these two effects, a larger sample size would be necessary to achieve more precise estimates.

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Erweiterte Zusammenfassung

Messungen der Biege- und Torsionssteifig-keit an Tibia- und Radius-Knochen von Pferden

In dieser Untersuchung wurden statische Messungen an langen Röhrenknochen von Pferden ausgewertet, welche in einer größeren Studie zur Bestimmung des Bruchverhaltens und des Widerstandes gegen schlagartige Belastung verwendet wurden. Ergänzend zu morphologischen und anderen mechanischen Charakterisierungen ging es bei der vorliegenden Teilstudie um die Bestimmung der Steifigkeit des Knochens unter quasi-statischer Belastung. Das Ziel war es die Biege- und Torsionssteifigkeit des zentralen Teils der Knochen zerstörungsfrei zu bestimmen und die Untersuchung eines möglichen Alters- und Geschlechtseinflusses auf diese Steifigkeitswerte.

Insgesamt wurden 56 Knochen von 15 Pferden (Tibiae und Radii) zuerst unter Torsionslast getestet und anschließend 55 Knochen davon unter Drei-Punkt-Biegung geprüft. Ein maximales Torsionsmoment von 150 N × m und ein maximales Biegemoment von 920 N × m wurden in Stufen aufgebracht. Die Deformation des Knochens wurde sowohl bei der Belastung als auch bei der Entlastung aufgenommen um mögliche Hysterese-Effekte zu erfassen. Die gemessenen Biege- und Torsionssteifigkeiten beider Knochentypen wurden zuerst rein deskriptiv beschrieben. Dabei wurden die beiden Werte nach Knochentyp (Radius versus Tibia), nach dem Alter des Pferdes (gruppiert in junge Tiere, mittelalterliche und alte) sowie nach dem Geschlecht unterschieden. Weitere Unterscheidungsmerkmale, wie die Seite (links oder rechts), die Rasse und die Verwendung des Pferdes (Rennsport versus andere Verwendungen, wie Freizeit) wurden nach einer Voruntersuchung wieder fallen gelassen. Der Effekt des Alters und des Geschlechts auf beide Steifigkeitswerte wurde anschließend mit multivariabler linearer Regression (linear mixed effects regression) modelliert und auf deren statistischen Signifikanz hin geprüft. Während unter Biegebeanspruchung eine leichte Hysterese in der Last-Deformations-Funktion, hervorgerufen durch lokales Eindrücken bei der Lasteinleitungsstelle und bei den Auflagern, festgestellt wurde, deckte sich unter Torsion die Entlastungs- mit der Belastungshalbschleife.

Die Biegesteifigkeit der Tibia-Knochen lag im Durchschnitt bei 6.813 N/mm (Kraft pro Millimeter Verschiebung), was 11 % höher liegt als die Biegesteifigkeit der Radius-Knochen (6.130 N/mm). Die Torsionssteifigkeit der Tibiae war 24 % höher als die der Radii mit 2.36×10^6 statt 1.90×10^6 N × m (rad/mm) (Torsionssteifigkeit pro Verdrehung in Radians genormt auf die Länge des Torsionsstabes, hier des Abstandes zwischen den Referenzquerschnitten, an denen die Verdrehung gemessen wird). Auch das Regressionsmodell zeigt einen deutlichen Unterschied zwischen den beiden Knochentypen (Tibia versus Radius). Das Modell zeigt zudem einen Trend zu höherer Steifigkeit bei Wallachen im Vergleich zu Stuten (3.1 % für Tibia unter Biegung, 13.7 % für Tibia unter Torsion, 12.1 % für Radius unter Biegung, 16.5 % für Radius unter Torsion) und eine abnehmende Steifigkeit mit dem Alter. Die Daten lassen vermuten, dass sich bei beiden Steifigkeiten ein Alters- und ein Geschlechtseffekt überlagern. In einer andern Studie, welche die genau gleiche Stichprobe von Knochen auf die Mikrostruktur des Knochenmaterials hin untersucht hat, konnte ein signifikanter Alterseffekt auf die Knochendichte nachgewiesen werden. Hingegen zeigte sich bei der Knochendichte kein Geschlechtseffekt. Wir vermuten, dass der Einfluss des Geschlechts auf die Knochensteifigkeit über einen Größeneffekt zustande kommt: Wallache sind in der Regel größer als Stuten, wodurch angenommen werden kann, dass auch deren Knochen größer sind. Von größeren Knochen kann gemäß klassischer Mechanik des Biege- resp. Torsionsstabes eine höhere Steifigkeit erwartet werden. Diese Zusammenhänge sollen in einer weiteren Studie anhand der gleichen Knochen-Stichprobe vertieft untersucht und mit den Steifigkeitsdaten korreliert werden.

Schlüsselwörter: Knochen / Pferd / Biegung / Torsion / Steifigkeit / Orthopädie