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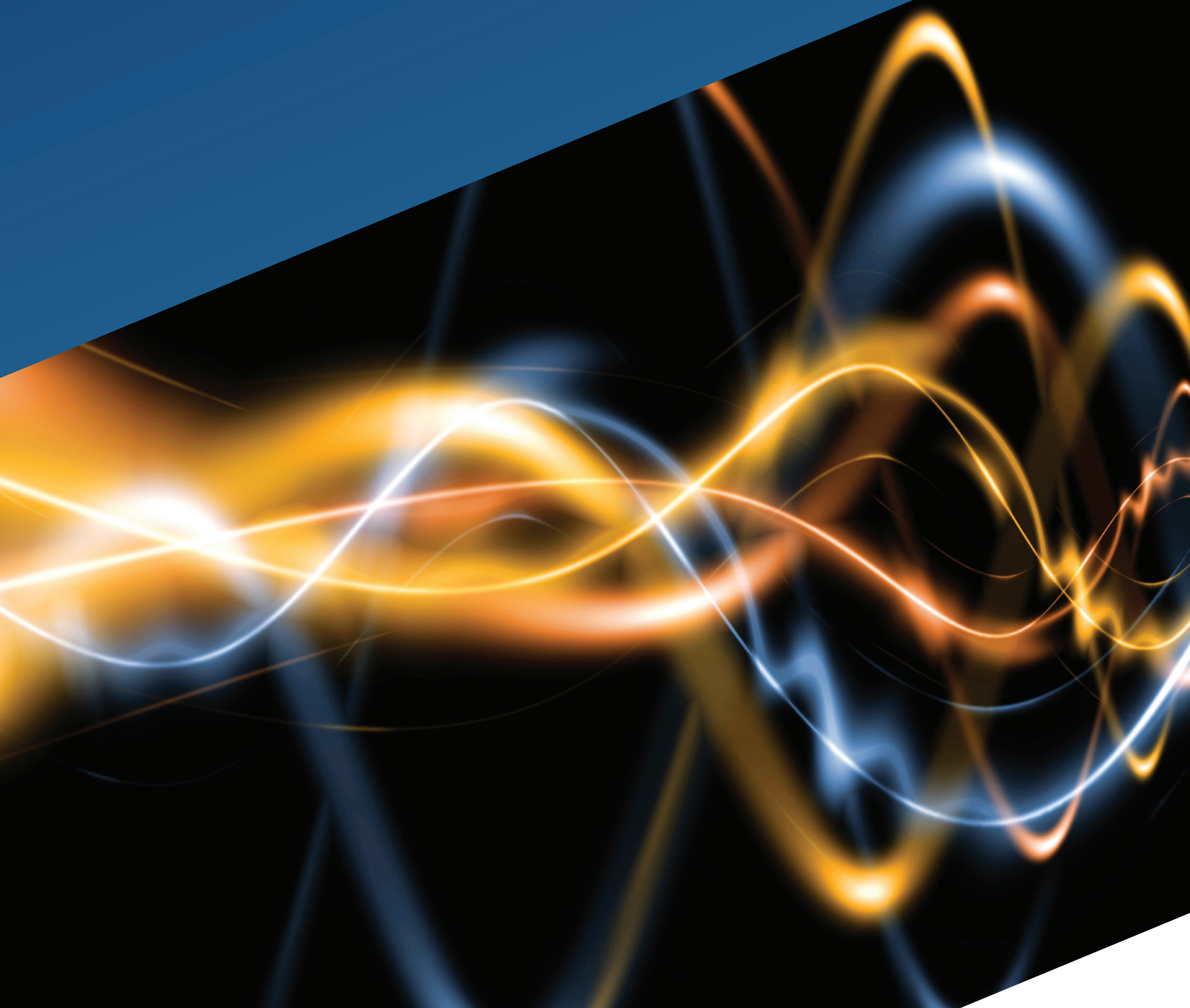

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CAN VIBRATION STATISTICS OF AN IDEALISED SINE WAVE BE USED TO EXAMINE FATIGUE PROPERTIES OF PORCINE TRABECULAR BONE?

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Abstract

Fatigue testing on trabecular bone has been performed throughout the years, the data contained could be of use to researchers attempting to find a qualitative link between whole-body vibration and spinal damage. 10 porcine trabecular cores were testing under fatigue loading at 2Hz with varying normalised stress values. A sample specific idealised sine wave was created to simulate comparable data to those found in fatigue papers. The idealised sine wave created a cascading error meaning no meaningful data could be unlocked. Examining fatigue and vibration in-vitro requires careful data logging of the acceleration component, the level of which is not achievable from the results typically found in journal papers.

1. Introduction

Low back pain (LBP) is a medical condition thought to be caused by damage to the tissues of the spinal column. It is thought that whole-body vibration (WBV) has a contributing factor to LBP over the course of a person's life in relation to their exposure. Certain occupations have been linked to an increased risk of LBP which coincides with an increased exposure to vibration (Manchikanti 2000) however the general prevalence of LBP within the general population is so large (Walsh et al. 1989) it is difficult to ascribe a relationship with WBV. As of yet there has been no direct cause and effect clearly defined from WBV.

The consensus within legislation is to lower exposure to WBV in an attempt to reduce the overall incidence of LBP. UK legislation on the control of WBV is based on assessing the severity of vibration in relation to frequency, exposure and acceleration, the main body of legislation being the Control of Vibration at Work Regulations 2005 (CVWR) (HSE 2005). The method for assessment used within was first standardised in ISO 2631-1 (ISO 1997), amongst others. The main methods used are Root Mean Squared (RMS) and Vibration Dose Value (VDV). As this paper examines only axial loading in the z-axis the methods will be detailed specifically in that axis. RMS is calculated through analysis of the vibration signal as show in Equation 1

$$RMS = \left[\frac{1}{T}\int_0^T a_w^2(t)dt\right]^{\frac{1}{2}}$$

Equation 1: RMS calculation

Where,

T is the time period observed (s)

$a_w(t)$ is the instantaneous weighted acceleration (ms^{-2})

The VDV is a cumulative vibration statistic of the fourth order and is calculated using Equation 2 below.

$$VDV = \left\{ \int_0^T [a_w(t)]^4 dt \right\}^{\frac{1}{4}}$$

Equation 2: VDV calculation

Where VDV is the Vibration Dose Value ($ms^{-1.75}$)

As VDV is cumulative and increases with exposure to vibration, it can be more useful to examine the daily exposure VDV_{exp}

$$VDV_{exp} = VDV \left(\frac{T_{exp}}{T}\right)^{1/4}$$

Equation 3: VDV_{exp} calculation

Where,

VDV_{exp} is the 4th order daily vibration exposure ($ms^{-1.75}$)

T_{exp} is the length of time exposed to the vibration signal in a given day (s)

The vibrational limits described in CVWR are much more lenient than those introduced in the ISO standard 2631-1 as shown in **Error! Reference source not found. Error! Reference source not found.**.

Table 1: Comparison of WBV Limits between ISO 2631-1 and CVWR

	Lower bound (RMS $a_{w(8)}$ ms^{-2})	*Upper bound (RMS $a_{w(8)}$ ms^{-2})*
ISO 2631-1	0.43	0.87
CVWR	0.5	1.15

CVWR also does not provide limits using the VDV method unlike the EU regulation 2002/44/EC (Directive 2002) which this is a national transposition of.

Usage of RMS is problematic as it is only a second order statistic. This means that short shock loads within examined time history, which are assumed to be more damaging, are weighted the same as vibrations of a lower magnitude. VDV, on the other hand, is a cumulative statistic of the 4th order. As it is a 4th order statistic, is more sensitive to the short sharp acceleration loads of shock more than RMS.

Research into the fatigue failure of trabecular bone has been examined for many years. Studies have been conducted into areas including the cycles to failure (Moore and Gibson 2003), primary methods of damage accumulation (Moore, O'Brien, and Gibson 2004), micro damage (Goff et al. 2015) and the effects of sample orientation (Haddock et al. 2000). A selection of these papers has been collated into **Error! Reference source not found. Error! Reference source not found.**.

Table 2: Axial trabecular fatigue testing

Author	*Year*	*Signal*	*Test Conditions*	*Test end conditions*
Lambers [1]	2013	Sine	σ/E_0=0.0035	Different fatigue phases
Rapillard [2]	2006	Sine	16-90% UCS	40% reduction of E_0
Moore[3]	2003	Sine	σ/E_0=0.005 - 0.008	0.8,1.1,1.3,1.65,2,2.5% - e
Haddock[4]	2004	Triangle	σ/E_0=0.026 - 0.07	σ/E0 = Failure
Dendorfer[5]	2008	Triangle	σ/E_0=0.0022 - 0.00147	"Catastrophic failure"
Cheng[6]	1992	Sine	0.29-0.45% e	Until failure
Ganguly [7]	2004	Sine	σ/E_0=0.005 - 0.009	Until prescribed strain met
Moore [8]	2004	Sine	σ/E_0=0.0065 - 0.0095	Fracture or -5% e
Haddock [9]	2000	Sine	σ/E_0=0.4 - 0.5	Fracture

[1] (Lambers et al. 2013), [2] (Rapillard, Charlebois, and Zysset 2006), [3] (Moore and Gibson 2003), [4] (Haddock et al. 2004), [5] (Dendorfer et al. 2008), [6] (Wen and Cheng 1992), [7] (Ganguly, Moore, and Gibson 2004), [8] (Moore et al. 2004), [9] (Haddock et al. 2000)

Where σ/E_0 is the normalised stress, UCS is ultimate compressive stress and e is strain.

The mechanical properties of trabecular bone is highly sample specific and so normalised stress is used to reduce the scatter caused by this large variation.

The tests conducted predominantly use sine or triangle waves with a prescribed testing frequency and boundary condition; this allows for an estimation of the RMS and VDV. The wealth of data contained in those papers may be invaluable for researchers looking to examine the health effects of vibration. Is it possible then, to generate a synthetic waveform based upon the data contained within the paper?

As it stands heath guidance as presented ISO 2631-1 is nothing more than a simple test of whether exposure to vibration can be expected to be harmful. They are based on qualitative studies and occupational surveys. There is a need to examine a whether a quantitative link exists between vibration exposure and spinal damage.

2. Materials and Methods

Cylindrical samples aligned with the anterior/posterior plane were taken from porcine vertebral bodies of freshly butchered animals using a 9mm diamond tipped coring tool. Marrow was removed using a high pressure water jet. The samples were kept frozen at -20ºc and only thawed and rehydrated 30 minutes before testing. PVC end caps were attached to the free faces of the samples using cyanoacrylate adhesive to minimise end effect artefacts (Cook 2005). The resulting specimens were approximately 25mm long, 15mm between the end caps.

Testing was performed on a servo-hydraulic testing rig (Dartec, HC-25) under force control. Specimens were placed between a self-levelling upper platen and rigid lower platen. Samples were kept moist throughout testing with a directed water jet at a constant 38ºC. A 5kN load cell was used to record the force data and an extensometer with a 6mm nominal gage length was used to record strain. A schematic of the test setup is shown in Figure 1.

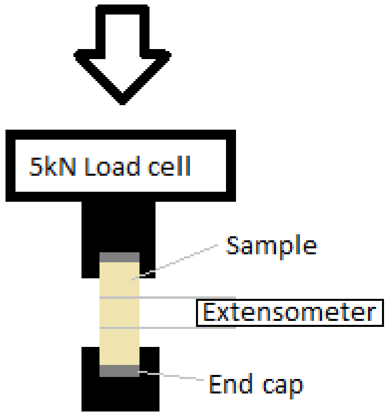

Figure 1: Testing schematic

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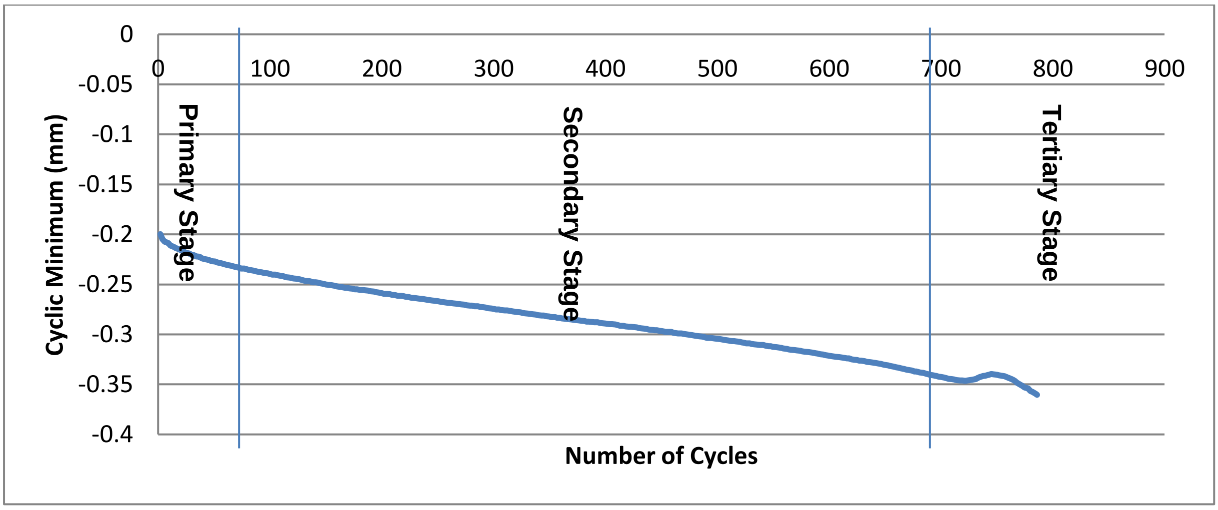

Figure 2: Typical test. Specimen shows the three stages of fatigue. Primary stage, where the strain increase decelerates. Secondary stage, platuea with slowly increasing strain. Tertiary stage, strain accelrates until specimen failure.

Before testing, samples were subjected to 20 preconditioning cycles of 10-50N at a frequency of 2Hz. The initial stiffness was taken from a linear fit of the Force/Extension graph of cycles 12-16. The extensometer was filtered at 5Hz to remove temporal artefacts over this examination window. The stiffness was then converted into initial modulus using the cylindrical area and gage length of the sample

Porcine cylindrical samples were tested at 2Hz from 10N to a given normalised stress value and stopped when a prescribed failure of e=0.4% in the extensometer gage length was recorded.

Throughout testing the number of cycles as well as the cyclic maximum and minimum values from the load cell and extensometer were recorded an example of this is shown in Figure 2. Four cycles were recorded in detail starting at every y^3 cycle, where y is the capture number. All data capture was performed on the testing machine at a sampling frequency of 500Hz.

Once specimen failure was reached the number of cycles to failure (N_f) was recorded. The peak to peak displacement was estimated using $x = \frac{F}{k_0}$, where x is the peak to peak displacement, F is the force applied and k_0 is the initial stiffness recorded. This is merely as estimation as it assumes that the sample stiffness does not change throughout the test, which is not observed through actual testing.

Using the estimated peak to peak displacement, it is possible to estimate the acceleration through Equation 4.

$$a_{pk} = \frac{2\pi^2 f^2 x}{G}$$

Equation 4: Relationship between acceleration, frequency and peak to peak displacement

Where,

a_{pk} is the peak acceleration in ms^{-2}

f is the frequency in Hz

G is an acceleration constant of 1000 mm/s^2

Sine waves were created in over from 0 seconds until $N_f \times f$ seconds with a sampling frequency of 500 Hz, the same sampling frequency used to record the detailed cycle data. The acceleration was weighted as per ISO 2631-1. From this sine wave RMS, VDV and VDV_{exp} were calculated. For the analysis T was set to the duration of test and T_{exp} was set to an 8 hour reference.

All and sine wave generation and analysis was performed on a commercial software package (MATLAB R2017, The MathWorks Inc., Natick, MA, 2017).

3. Results and Discussion

Using a specimen which is part of a larger unit makes comparison between real world exposure and ex-vivo studies difficult, however comparisons can be made between the samples.

Table 3 shows the statistics obtained. Idealised sine wave statistics are shown in mm for convenience.

Table 3: Vibration statistics per sample

#	***E_0*** (MPa)	***σ/E_0***	N_f	*x (mm)*	a_{pk} (mms^{-2})	*RMS* (mms^{-2})	*VDV* ($mms^{-1.75}$)	VDV_{exp} ($mms^{-1.75}$)
1	1111	0.0113	30	0.0667	5.264	1.976	4.30	28.49
2	1175	0.0054	3456	0.0314	2.483	0.932	6.65	13.44
3	1025	0.0054	7800	0.0307	2.424	0.910	7.96	13.12
4	928	0.0068	786	0.0398	3.143	1.180	5.81	17.01
5	1064	0.0022	2611113	0.0132	1.044	0.392	13.92	5.36
6	1108	0.0106	49	0.0625	4.935	1.853	4.56	26.71
7	1187	0.0060	23760	0.0342	2.697	1.013	11.70	14.60
8	1694	0.0056	192	0.0316	2.493	0.936	3.24	13.50
9	1747	0.0038	43577	0.0226	1.782	0.669	8.99	9.64
10	953	0.0051	386705	0.0297	2.346	0.881	20.44	12.70

The values in Table 3 are not representative of the data seen from vibrational studies such as from marine seat pad accelerations. The relative displacements observed are at least an order of magnitude lower than those experienced in the field. The action value and limit values as described by the CVWR would not be met in a 24hr period if the values of RMS observed were used.

Figure 3 shows that as the normalised stress decreases the number of cycles to failure increases. It follows a power law where $N_f = 8 \times 10^{-13}(\frac{\sigma}{E_0})^{-0.7626}$ with an R^2=0.761. The 10 fatigue tests performed demonstrated a small spread in relation to number of cycles to failure and normalised stress this can be attributed to the number of samples tested causing a small scatter than what would be typically expected.

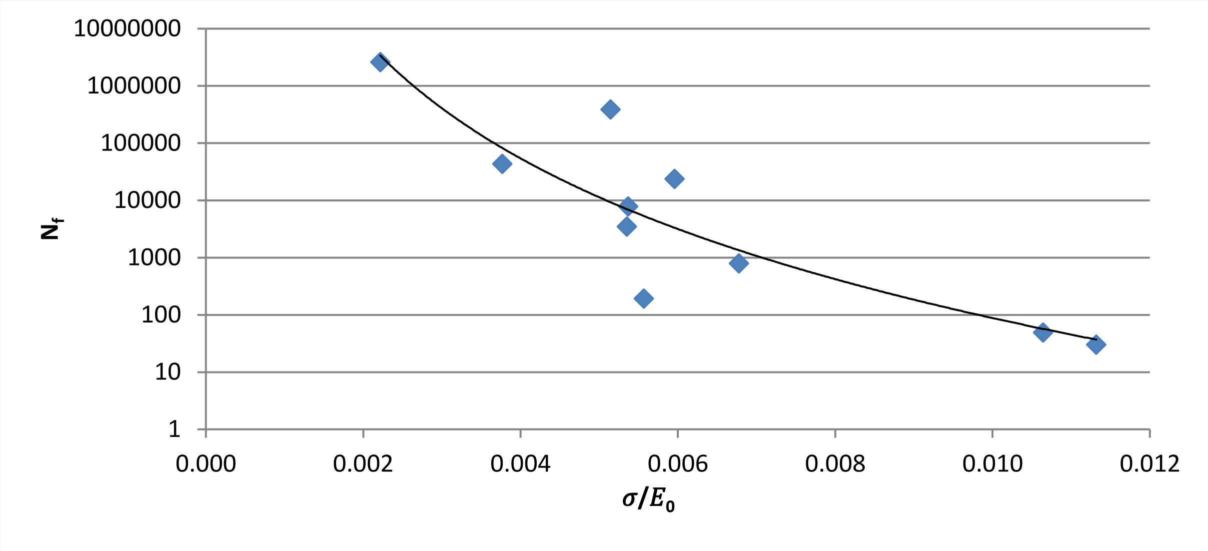

Figure 3: Number of cycles to failure vs Normalised stress

Figure 4 shows the relationship between the RMS from the idealised sine wave and against cycles to failure. It shows a downward trend; the lower the RMS the sample is exposed to the longer it takes to fail. The trend line shown follows the power law $N_f = 4096(RMS)^{-7.072}$ ($R^2 = 0.763$).

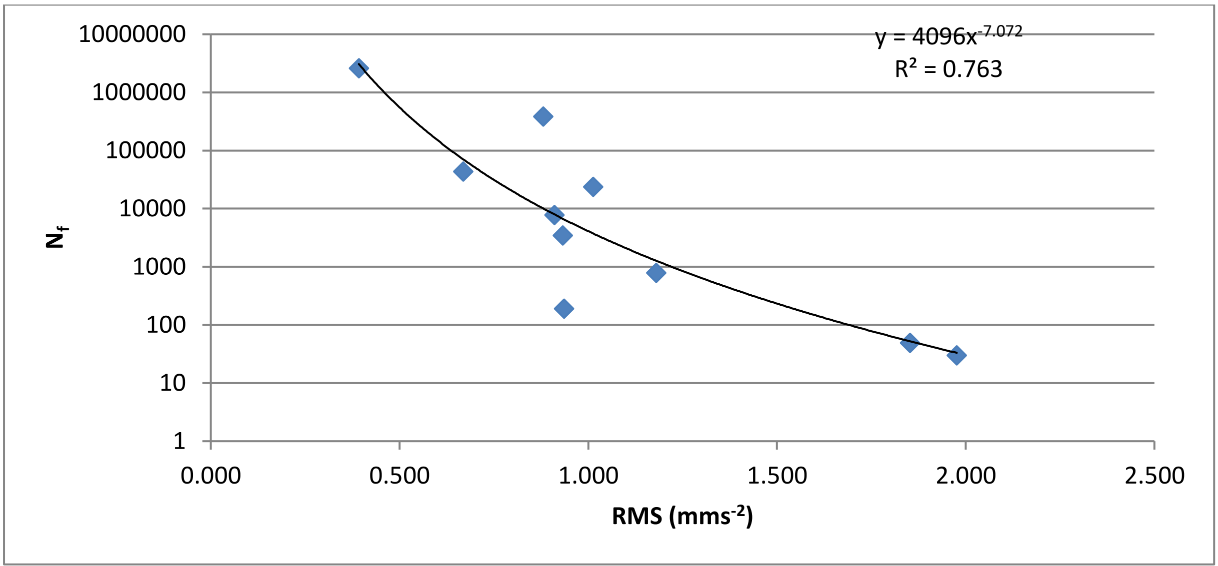

Figure 4: Number of cycles to failure vs RMS

Figure 5 shows that as VDV increases so does the number of cycles to failure. This is expected as VDV is a cumulative statistic and when the sample takes longer to fail, it is exposed to more vibration.

The best fit for Figure 5 is $N_f = 0.0266(VDV)^{-5.99}$ (R^2=0.8359)

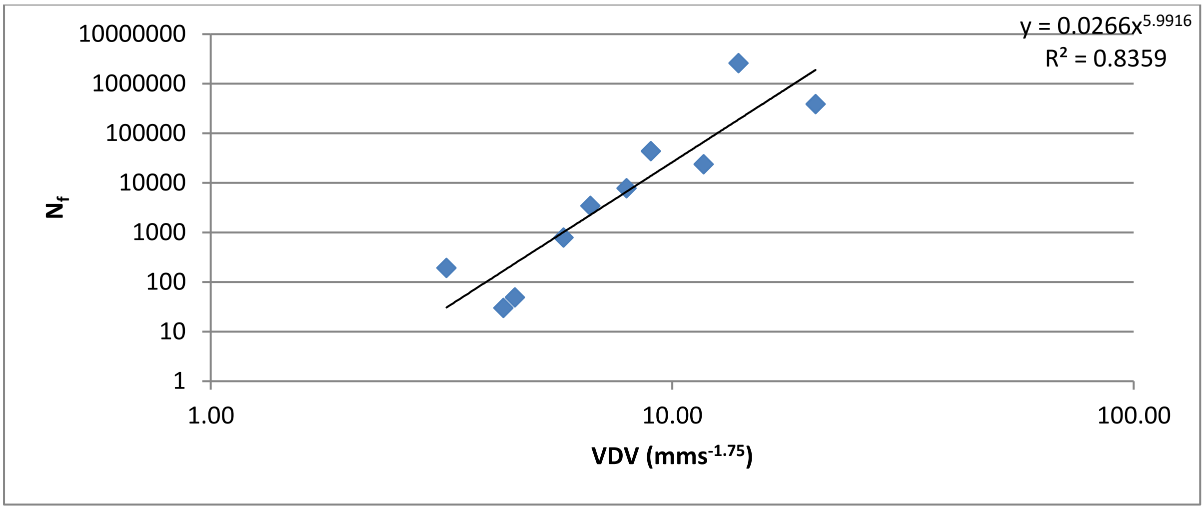

Figure 5: Number of cycles to failure vs VDV

Figure 6 shows the relationship between number of cycles to failure and VDV_{exp}. The shape is very similar to that obtained in Figure 3 and Figure 4.

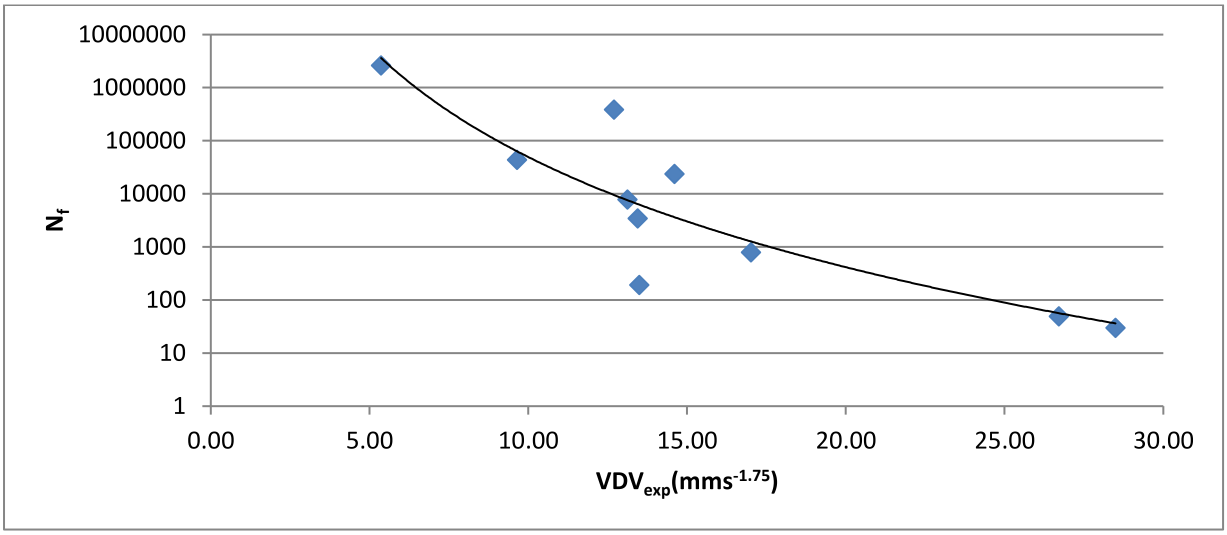

Figure 6: Number of cycles to failure vs VDV_{exp}

If these results are taken at face value, they show a link between RMS and damage of bone. This cannot be done as the statistics are generated from an idealised sine wave which makes the assumption that the stiffness of the specimen does not change, when it has been previously shown to decrease after fatigue testing (Moore and Gibson 2003) This discrepancy leads on to further assumptions; that the peak to peak displacement the sample undergoes is constant and therefore the acceleration also remains constant. This leads the RMS and VDV_{exp} values to be based off the initial stiffness values giving a graph which follows Figure 3 almost exactly.

4. Conclusion

For an idealised sine wave with one frequency, vibration statistics hold no useful data; it only tells us what we already know. Using an accelerometer to measure the acceleration rather than attempting to back calculate from an ideal a sine wave would greatly increase the accuracy of the data. Without the acceleration data as well as the specific number of cycles to failure for each sample it is difficult to draw any meaningful conclusions from a statistical analysis from this data let alone the data condensed into the papers referred to in Table 2.

Further work could be done at examining the fatigue failure of human tissue from a vibration perspective. If multiple sine waves with varied frequency content were used it would allow an examination of the frequency weighting as used in ISO 2631-1. A shaker table playing back white noise with a prescribed RMS and frequency content could be used to simulate fatigue on real world scenarios.

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