Original Research

Investigation into the effect of static stretching on the active stiffness and damping characteristics of the ankle joint plantar flexors

D. Glenn Hunter, Vince Coveney and Jonathon Spriggs

Objective: The purpose of the study was to investigate the effect of static stretching on the active stiffness and damping characteristics of the ankle joint plantar flexors. *Design*: The study was an experimental design. *Background*: Flexibility has static and active components. Little information is available regarding the effect of static stretching on the active stiffness of the muscle tendon unit. This may have relevance in relation to muscle tendon unit injury and the assessment of flexibility. *Methods*: Pre- and post-intervention free oscillation data representing active stiffness was obtained in 30 subjects using applied masses equivalent to 30% of the subject's maximal voluntary contraction (MVC). The control group ($n = 15$) rested between measurements, the experimental group performed 10 $\times$ 30 second static stretches for the ankle joint plantar-flexors. *Results*: No statistically significant differences were found for stiffness values ($P = 0.71$ 95%; CI – 1503–2172) and damping values ($P = 0.94$ 95%; CI – 0.0272–0.0195) between the control and stretching group. The trend was an increase in both parameters following stretching. *Conclusions*: The results imply that static stretching had no statistically significant effect on the active stiffness or damping characteristics of the muscle tendon unit as measured with applied masses equating to 30% maximal voluntary contraction. The low statistical power of the study should be considered in evaluating the results. *Relevance*: Flexibility is a construct with different components of measurement. Studies typically relate static flexibility measurements or exercises to injury with conflicting outcomes. This study suggests that static stretching may have no effect on active stiffness of the ankle plantar-flexors and that these findings may have value in the design of stretching programs and in aetiological studies pertaining to flexibility. © 2001 Harcourt Publishers Ltd

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Introduction

Stretching is used almost universally as a precursor to sporting activity, with the literature suggesting many positive, though mainly unsubstantiated, effects of this practice (Gleim & McHugh 1997). A frequently claimed benefit relates to injury prevention with the ubiquitous notion that 'tight' muscles are more likely to be strained (Worrell & Perrin 1992, Best 1995). The assumption is that stretching produces a more compliant muscle, which can be stretched to a higher ultimate strain and is therefore less susceptible to injury (Safran et al. 1998). Owing to the complex nature of sporting injury, such claims are difficult to substantiate from the available literature, however a number of prospective studies suggest that a relationship may exist (Pope et al. 1998, Ekstrand & Gillquist 1983, Lysens et al. 1991).

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Of note is the work of Pope et al. (1998) who studied 1093 army recruits and found that a simple measure of ankle dorsiflexion was a strong predictor of injury ($P = 0.03$), with poor flexibility being associated with 2.5 times the risk of injury in relation to average flexibility, and up to 8 times the risk when associated with high flexibility.

The methodological difficulties of exploring any potential relationship between stretching and injury prevention lie in the multifactorial nature of the aetiology of injury, the use of differing stretching regimes, and the measurement of the effects of these exercises on the properties of the muscle tendon unit (MTU). With regards to the latter, measurements involve assessing the ability of the MTU to lengthen and this property is referred to as muscle flexibility. The majority of published studies assess the effect of stretching protocols by using measurements of static flexibility with the joint range of motion or angle being assumed to equate to muscle length. These measurements may not be valid as the measured joint angle may not accurately represent the ultimate MTU length, and passive elongation of the MTU fails to represent the state of the MTU during dynamic activity. A more functional measurement may be that of dynamic flexibility where the stiffness of the MTU can be measured passively or actively.

Passive stiffness is measured by quantifying the joint angle at the same time as passive torque generation with the slope of the torque angle being proportional to the stiffness. (Gadjosik 1991). Active stiffness may be measured in vivo by using a free oscillation technique where the loaded MTU is gently perturbed and the damped free response of the system is recorded (Shorten 1987). This technique has been used in vivo by a number of authors (Oatis 1993, Jennings & Seedholm 1998, McNair et al. 1992, Wilson et al. 1994) who have observed stiffness load characteristics similar to that observed in isolated muscle preparations (Cavagna 1970). Walshe et al. (1996) have shown the method to be valid and reliable. In relation to injury, the measurement of active stiffness may be a more valid measure than passive flexibility because the MTU is active during the measurement, and the active stiffness determines the effectiveness of force transmission through the MTU.

McNair & Stanley (1996) used this approach to investigate the effect of static stretching, running, and stretching plus running on the active stiffness of the ankle plantar flexors. They found that the active stiffness values decreased for both the running and stretching plus running group, but increased from 15212 N/m to 15432 N/m in the stretching group. Though this increase is small, these results are surprising in that they are contrary to the common assumption that stretching decreases muscle stiffness. Also, McNair et al. (1996) found that though the active stiffness increased the static flexibility measured via the angle of ankle dorsi-flexion also increased, implying decreased passive stiffness. These results, if valid, suggest that static stretching may decrease the stiffness of the MTU thus increasing the static flexibility, but increase the stiffness of the MTU during dynamic activity.

Because the work of McNair et al. (1996) is the only published study the authors could find to identify this effect, and of the potential implications that these results may have on stretching protocols, the authors decided to replicate part of this study to contribute to the assessment of the validity of these findings. It was also decided to extend the analysis to include the effects of stretching on the damping (energy absorption) ratio of the MTU, as a change in damping may provide a plausible mechanism for stretching reducing the risk of injury. Thus the aim of this study was to investigate the effect of static stretching on the active stiffness and damping characteristics of the ankle joint plantar-flexors.

Method

Subjects

Thirty subjects were recruited from an advertisement. Their mean age, height and weight are presented in Table 1. At the time of the study, all subjects were healthy and without injury. The University of the West of England Ethics committee granted ethical clearance for this study, and all subjects

Table 1 Subject characteristics (mean and [standard deviation])

	Age (years)	Height (m)	Weight (kg)
Males ($n = 15$)	33.7 (6.8)	1.6 (0.5)	78.5 (13.3)
Females ($n = 15$)	40.0 (6.9)	1.7 (0.05)	73.1 (13.9)

gave their informed consent. Subjects were randomly allocated to either the control ($n = 15$) or stretch group ($n = 15$).

Apparatus

A Kistler force plate (type 9281B12) was configured to the International Society of Biomechanics (ISB) coordinate system. Signals were sampled at 500 Hz to provide vertical force histories relating to the calculation of the maximal voluntary contraction (MVC) and for the free oscillations of the lower leg. A wooden block was placed on the force plate and used to support the forefoot, leaving the heel free to oscillate when the leg was set in motion (Fig. 1).

A schematic of the general arrangement is presented in Figure 1. The lever support system was constructed to support the applied mass and to provide resistance for the calculation of the MVC. A platform was placed on top of the knee to support the applied mass for the collection of free oscillation data. For the calculation of the MVC, the hinge on the system was locked so that the subject exerted an isometric plantar-flexion muscle contraction with the knee pressing up against the effectively immovable platform.

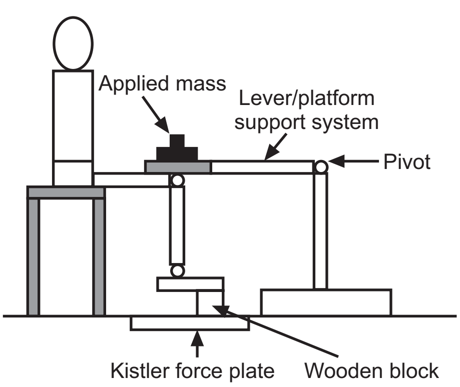

Fig. 1 Experimental position for the collection of free oscillation data.

Procedures

Data collection involved three stages:

1. Calculation of the MVC

Using their right leg, subjects sat as in Figure 1. The hinge on the lever system was immobilized and the subjects were asked to attempt to plantar-flex their ankle maximally for a period of 20 seconds. Verbal encouragement was given. The MVC was taken as the peak force generated during this time. The applied masses to be used for the collection of free oscillation data were referenced to each subject's MVC, with values of 30% MVC being chosen. The choice of 30% MVC was based on the method of McNair et al. (1996) who cited Cicotti (1994) to support the claim that this is representative of the muscle activation levels observed during gait activity.

2. Calculation of free oscillation data

The mass was applied to the platform resting on the subject's knee and the subject was asked to maintain a steady state muscle contraction for 10 seconds. The subject was asked not to react to any stimulus to reduce the possible neural responses to the applied perturbation (Gottlieb & Agarwal 1998). After approximately 2 seconds, a small downward impulse (approximately 100N in magnitude) was applied manually to the mass to set the leg into oscillation. A second impulse was then applied and the results of the two oscillation readings were averaged. This procedure was chosen to replicate the experimental procedure used by McNair et al. (1996).

3. Intervention

Between each pair of measurements, the control group remained sitting for 10 min with the ankle in plantar grade and the plantar flexor muscles relaxed. The stretch group performed 10×30 seconds static stretches as in Figure 2. The stretches were held at the point of mild to moderate discomfort and each stretch was followed by a 30 second rest period.

Data analysis

Fourier analysis was performed on all the force plate data, with frequencies >25 Hz being

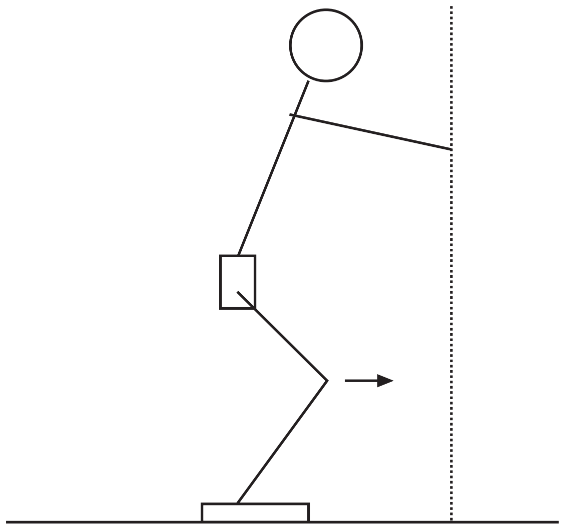

Fig. 2 Stretching position held for 30 seconds × 10.

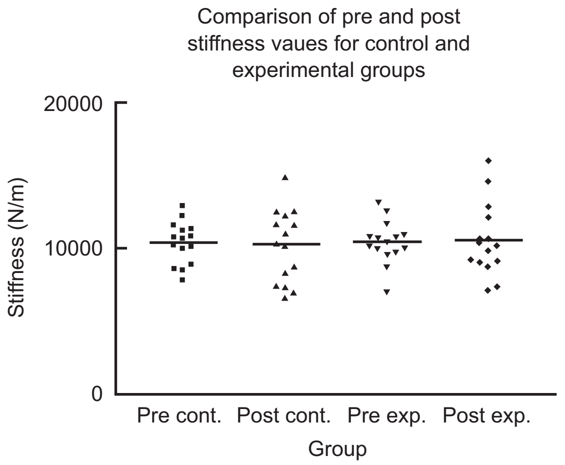

Fig. 3 Pre and post stiffness values for control and

filtered out of the reconstructed signal to reduce noise. After calculating the datum signal, the values of force and time period for the first cycle were determined. Use of Equations (3) and (4) (see Appendix) enabled values for the damped frequency of oscillation (f_d) and logarithmic decrement (δ) of the system to be determined. Stiffness values (k) were calculated via Equation (2).

Results

No statistically significant difference was found between male and female subjects for active stiffness values ($P = 0.06$, alpha 0.05, 2-tail) and

Table 2 Stiffness in units of N/m pre and post intervention

Group	Mean	Standard deviation	95% confidence interval
Pre control	10330	1431	9533–11120
Post control	10190	2466	8829–11560
Pre stretch	10400	1471	9584–11210
Post stretch	10530	2447	9174–11880

Table 3 Damping ratio pre and post intervention

Group	Mean	Standard deviation	95% confidence interval
Pre control	0.2082	0.053	0.1789–0.2375
Post control	0.2229	0.034	0.2040–0.2417
Pre stretch	0.1933	0.094	0.1413–0.2452
Post stretch	0.2240	0.041	0.2011–0.2469

therefore male and female data were aggregated for the purpose of the analysis.

Stiffness and damping values pre and post intervention are presented in Tables 2 and 3 and Figures 3 and 4.

Unpaired t-tests (alpha 0.05, 2-tail) were used to compare the control and stretching groups pre and post intervention, with no statistically significant difference being found in both cases (Table 4).

Reliability analysis using paired t-tests and Pearson's correlation coefficient were conducted on the measurement of active stiffness using 10 subjects; the results are presented in Table 5.

Discussion

The aim of this study was to investigate the effect of static stretching on the active stiffness and damping characteristics of the ankle joint plantar-flexors. The results imply that 5 min of static stretching had no statistically significant effect on the active stiffness or damping coefficient of this muscle group, with the trend being an increase in both these parameters post stretching. The increase in active stiffness seen post stretching duplicates the findings of McNair & Stanley (1996), although the stiffness measurements obtained in this study were lower.

Table 4 Unpaired *t*-test values

Variable	*P* value	95% confidence interval
Stiffness:		
Pre control vs pre stretch gp	0.89	−1012–1158
Post control vs post stretch gp	0.71	−1503–2172
Damping:		
Pre control vs pre stretch gp	0.60	−0.072–0.042
Post control vs post stretch gp	0.94	−0.0272–0.0295

Table 5 Reliability analysis for stiffness values measured in N/m

Measurement	Mean	SD	*P*	r
Test 1	14280	21916	0·0001	0·71
Test 2	22730	71412		

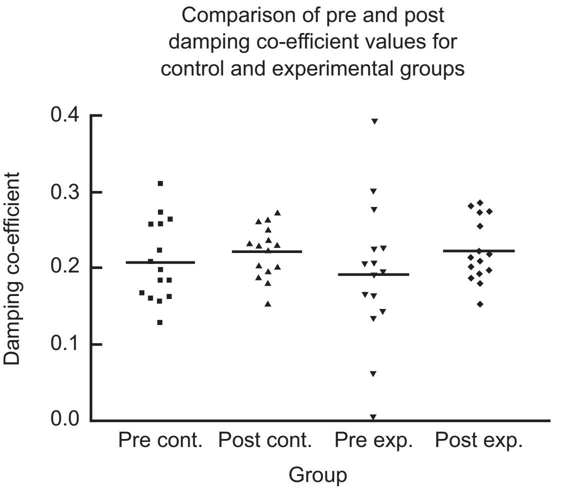

Fig. 4 Pre and post damping coefficient values for control and experimental groups.

The damping coefficient increased following the stretching protocol, but a similar increase was also evident in the control group. Damping relates to energy absorption (Thompson 1981) and therefore an increase in damping properties may relate to an improved ability of MTU to absorb energy and, therefore, reduced injury risk. However, the increase was not statistically significant in relation to the control group. As the experimental procedure involved muscular activity in supporting the weight prior to the oscillation, it is plausible that muscle contraction alone alters the damping characteristics of the MTU; this is an area for further study.

From the perspective of stretching, the response of the MTU to a stretching (tensile) force is regulated by noncontractile, contractile and neurophysiological mechanisms (Shrier 1999). The reflex components appear to influence the active stiffness of the MTU more at lower levels of muscle contraction, reaching zero close to the MVC of the muscle (Toft 1995). The non-contractile tissues predominantly regulate the mechanical properties of the MTU during static stretching (Magid & Law 1985, Horowits et al. 1986), whereas the active stiffness of the MTU is though to be dependent on the number of actin and myosin cross-bridges (Sinkjar et al. 1988, Rack & Westbury 1974). On this basis, static stretching is likely to address the non-contractile components of the MTU, resulting in an increase in static flexibility, but this change is masked during the assessment of active stiffness due to actin and myosin cross bridge formation. The discrepancy between passive flexibility and active stiffness has been alluded to by the authors elsewhere (Hunter & Spriggs 2000).

From a clinical perspective it may be hypothesized that static stretching has little effect on the prevention of injury that occurs when the MTU is active, but may be relevant for injuries that occur when the MTU reaches a certain length. It may be that stretching techniques that involve muscle contraction, such as proprioceptive neuromuscular facilitation, has a greater effect on active stiffness and on injuries related to excessive muscle force rather than length. In this case the muscle activity involved in a technique such as hold relax may affect both the contractile and non-contractile components of the MTU, resulting in a reduction in active stiffness. On a similar vein eccentric exercise which involves muscle activation combined with muscle lengthening may reduce active stiffness and affect the damping characteristic of the calf complex. If shown to be a valid hypothesis, this may provide a plausible rationale for the use of eccentric exercise in the management of Achilles tendonopathy (Alfredson et al. 1998). The effect of dynamic stretching procedures on active stiffness is a proposed area for further study.

A flaw in the current study was that in contrast to McNair & Stanley (1996) the authors did not perform electromyographic readings during the trials to identify co-contraction or active oscillation. Pilot trials were conducted to identify the trace profile during active oscillation and it was felt that these traces would be easy to identify and therefore eliminated from the study. Also in contrast to McNair & Stanley (1996), the authors did not measure the affect of the stretching protocol in terms of increased passive range post stretching. On this basis although the subjects were asked to stretch to the point of mild to moderate discomfort, the effect of this protocol on static flexibility cannot be determined.

The reliability of the study was moderate ($P < 0.0001$, $r = 0.71$). It is impossible to say whether this moderate rating reflects natural human variation or experimental error, although refinements in the method in terms of controlling the loading parameters and alternative subject positions for the test procedure merit exploration.

The value of 30% MVC was used to mimic McNair & Stanley (1996) who cited Cicotti (1994) who used electromyography (EMG) to identify muscle activation levels during the gait cycle. Inferences of force from EMG activity are dubious (Hof 1997), and the level of muscle activity in this study is likely to be low compared to dynamic sporting activity. It may be that stretching has an effect at greater levels of muscle recruitment and this is an area for further study.

The clinical implications of these findings must be guarded due to the low statistical power of this study. Given the mean stiffness difference of 340 N/m between the control and stretch groups, the effect size is low at 0.14 and a sample size of 816 in each group would be required to make this difference significant. Consequently there is a high possibility of a type II error in these results, where a statement that stretching has no significant effect is in fact incorrect. On this basis further studies with greater statistical power are required to validate these results.

Conclusion

The results imply that 10 times 30 second static stretches of the ankle plantar flexors have no statistically significant effect on the active stiffness or damping of this muscle group as measured at 30% MVC. These results support the findings of McNair & Stanley (1996), contributing validity to their results. From a clinical perspective it may be hypothesized that static stretching has no significant effect on the active stiffness of this muscle group and may therefore have limited effect on the prevention of MTU injuries that occur while the MTU is active. Stretching techniques such as proprioceptive neuromuscular facilitation which involve active muscle contraction may have a greater effect on active MTU stiffness although this hypothesis has yet to be tested. The reader is reminded to consider the low statistical power of the study in drawing hypothesis for clinical reasoning from these results. Further research is required to explore the contribution of contractile, non-contractile, and reflex parameters to MTU stiffness, and in terms of modelling MTU active characteristics over a range of loading parameters to assess the validity of the current findings.

References

Alfredson H, Oietila T, Johnsson P, Lorentzon R 1998 Heavy-load eccentric calf muscle training for the treatment of chronic Achilles tendonosis. American Journal of Sports Medicine 26 (3): 360–366

Best T M 1995 Muscle-tendon injuries in young athletes. Clinics in Sports Medicine 14: 669–686

Cavagna G A 1970 Elastic bounce of the body. Journal of Applied Physiology 29: 279–282

Ekstrand J, Gillquist J 1983 The avoidability of soccer injuries. International Journal of Sports Medicine 4: 124–128

Gadjosik R L 1991 Passive compliance and length of clinically short hamstring muscles of healthy men. Clinical Biomechanics June 6: 239–244

Gleim G W, McHugh M P 1997 Flexibility and its effects on sports injury and performance. Sports Medicine 24 (5): 289–299

Gottlieb G L, Agarwal G C 1998 Compliance of single joint elastic and plastic characteristics. Journal of Neurophysiology 59: 937–951

Horowits R, Kempner E S, Hisher M E, Podolsky R J 1986 A physiological role for titin and nebulin in skeletal muscle. Nature 323: 160–164

Hof A L 1997 The relationship between electromyogram and muscle force. Sportverletzug-Sportschaden 11: 79–86

Hunter D G, Spriggs J 2000 Investigation into the relationship between the passive flexibility and active stiffness of the ankle plantarflexor muscles. Clinical Biomechanics: in press

Jennings A G, Seedhom B B 1998 The measurement of muscle stiffness in anterior cruciate injuries – an experiment revisited. Clinical Biomechanics 13 (2): 138–140

Lysens R J, deWeerdt W, Nieuboer A 1991 Factors associated with injury proneness. Sports Medicine 12: 281–289

Magid A, Law D J 1985 Myofibrils bear most of the resting tension in the frog skeletal muscle. Science 230: 1280–1282

McNair P J, Stanley S N 1996 Effect of passive stretching and jogging on the series elastic muscle stiffness and range of motion of the ankle joint. British Journal of Sports Medicine 30: 313–318

McNair P J, Wood G A, Marshall R N 1992 Stiffness of the hamstring muscles and its relationship to function in anterior cruciate ligament deficient individuals. Clinical Biomechanics 7: 131–137

Oatis C A 1993 The use of a mechanical model to describe the stiffness and damping characteristics of the knee joint in healthy adults. Physical Therapy 73 (11): 740–749

Pope R, Herbert R, Kirwan J 1998 Effects of ankle dorsiflexion range and pre exercise calf muscle stretching on injury risk in army recruits. Australian Journal of Physiotherapy 44: 165–177

Rack P M H, Westbury D R 1974 The short-range stiffness of active mammalian muscle and its effects on mechanical properties. Journal of Physiology (Lond) 240: 331–350

Safran M R, Garrett W E, Seaber A V 1998 The role of warm up in muscular injury prevention. American Journal of Sports Medicine 16 (2): 123–129

Shorten M R 1987 Muscle elasticity and human performance. In: Van Gheluwe B, Atha J (eds). Current Research in Sports Biomechanics. Basel, Karger, pp 1–18

Shrier I 1999 Stretching before exercise does not reduce the risk of local muscle injury: a critical review of the clinical and basic science literature. Clinical Journal of Sports Medicine 9: 221–227

Sinkjar T, Toft E, Andreassen S, Hornemann B C 1988 Muscle stiffness in human ankle dorsiflexors: intrinsic and reflex components. Journal of Neurosciences 60: 1110–1121

Thompson W T 1981 Theory of vibration with applications, 2nd edn. London: Allen (George) and Unwin

Toft E 1995 Mechanical and electromyographic stretch responses in spastic and healthy subjects. Acta Neurologica Scandinavica (Suppl) 163: 311–315

Walshe A D, Wilson G J, Murphy A J 1996 The validity and reliability of a test of lower body musculotendinous stiffness. European Journal of Applied Physiology 73: 332–339

Wilson G J, Murphy A J, Pryor J F 1994 Musculotendinous stiffness: its relationship to eccentric isometric and concentric performance. Journal of Applied Physiology 76: 2714–2719

Worrell T W, Perrin D H 1992 Hamstring muscle injury: the influence of strength, flexibility, warm-up and fatigue. Journal of Orthopedic Sports Physical Therapy 16: 12–18

Appendix

The damped free oscillation can be modelled by following a second order linear equation

$$\frac{mdx^2}{dt^2} + \frac{cdx}{dt} + kx = 0 \qquad (1)$$

Where: x = position; g = gravitational acceleration; m = effective mass of the mass of the system.

Stiffness (k) is therefore calculated from the free oscillation data using the formula

$$k = 4\pi^2 f_d^2 m + c^2/4m \qquad (2)$$

Where: k = stiffness; m = mass; f_d = damped frequency of oscillation; c = coefficient of damping.

Assuming linear behavior, displacement (x) can be replaced by force (f) in Equation 1 and in the evaluation of the logarithmic decrement (eqn 2).

Specifically, calculation of k involves the following 3 stages:

1. m = applied mass (weights plus effective mass of the leg).
2. $f_d = 1/T$.

Where T = interval from peak 1 to peak 2 (Fig. 5)

3. Evaluation of c (involving iv sub stages)
   i. The logarithmic decrement (ζ) is calculated for one complete cycle of oscillation (Fig. 6).

$$\delta = \log_e(F1/F2) \qquad (3)$$

   ii. The damping ratio

$$\zeta = \frac{\delta}{\sqrt{(2\pi)^2 + \delta^2}} \qquad (4)$$

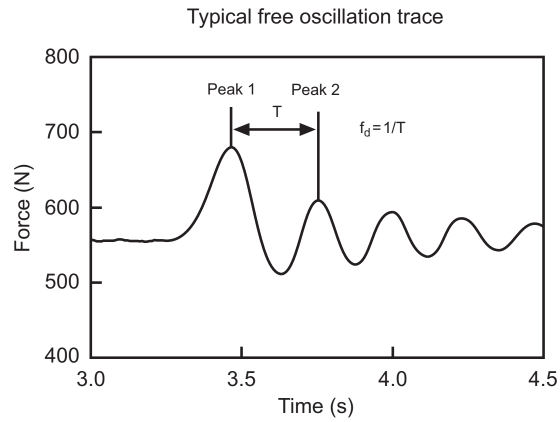

Fig. 5 Typical free oscillation trace showing the calculation of the time period.

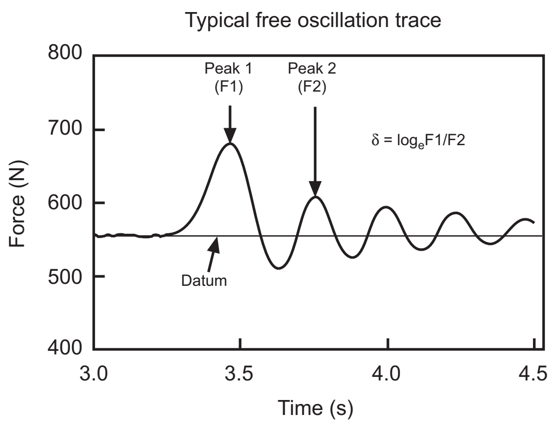

Fig. 6 Typical free oscillation trace showing the calculation of the logarithmic decrement.

   iii. The un-damped natural circular frequency (ω_o) is calculated by:

$$\omega_n = \frac{f}{\sqrt{1 - \zeta^2}} \qquad (5)$$

   iv. Damping coefficient

$$c = 2m\zeta\omega_n \qquad (6)$$

Further background on the theory of vibration can be obtained from Thompson (1981).