REVIEW OF HUMAN PERCEPTION OF WHOLE-BODY VIBRATION AND MECHANICAL SHOCK: THE IMPLICATIONS OF BIODYNAMIC NONLINEARITIES AND SOFT TISSUE

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Abstract

Previous studies have shown that the resonance frequencies apparent in the dynamic response of the human body tend to decrease with increasing excitation magnitude. However, many current standards assume that the human subjective and biodynamic responses to vibration and mechanical shock are the same at substantially different magnitudes of excitation. This paper aims to gather evidence, from human perception and biomechanical studies, that the nonlinear magnitude dependence of human discomfort is related to the nonlinearity in objective measurements primarily caused by soft tissue.

Studies are compared in two categories: i) subjective perception studies of whole-body vibration and mechanical shock; ii) experimental and analytical investigations examining the dynamic property of soft human tissue.

It was concluded that implementing the nonlinear mechanism of soft tissues into current human body models has the potential to improve the prediction of human physical and subjective responses to vibration. Predictive methods are particularly important for assessing and controlling health risks from high magnitude and high loading rate events such as mechanical shocks and impacts.

1. Introduction

We are exposed to motions all through our lives with different waveforms, durations, and magnitudes. An understanding of how motions are transmitted into and through the body is a prerequisite for understanding how vibration affects comfort and health. Key to this understanding is the fact that the transmissibilities and apparent mass show resonance frequencies that decrease with increasing excitation magnitude. Current British and international standards still assume human subjective and biodynamic responses to vibration and mechanical shocks to be the same at substantially different magnitudes of excitation (e.g. BSI 1987; ISO 1997, 2004). This assumption may be misleading when assessing and controlling exposure to vibration and mechanical shock.

In addition to the biodynamic studies, psychophysical studies have developed equivalent comfort contours from measurements of subjective discomfort. The assumption is often made that the risk of injury is related to the ‘motion to sensation system’, but there is no established relationship between discomfort and injury (e.g. Griffin, 1990).

The similarities between the subjective and biodynamic nonlinearities in the responses of the human body to shock and vibration has gradually received more attention (e.g. Matsumoto and Griffin, 2005, 2009; Ahn and Griffin, 2008; Miyuki and Griffin, 2006). Nonlinear responses have been reported in axes parallel to and orthogonal to the direction of excitation for seated (e.g. Nawayseh and Griffin,

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2003, 2005), standing (e.g. Matsumoto and Griffin, 1998; Subashi *et al*., 2006) and supine persons (Huang and Griffin, 2008a, 2008b), and with multi-axis excitations (e.g. Hinz *et al*., 2006; Mansfield and Maeda, 2007).

While the objective characteristics of statistically stationary vibration can be reasonably described by the frequency content and the average (second or fourth power) magnitude, these measures may not be adequate for abrupt motions with large and sudden variations in instantaneous amplitude (e.g. Lewis, 2007). Perception and tolerance of such transient motions is influenced by time-domain characteristics including shock direction (upward or downward), duration (equivalent frequency), onset rate, decay rate (damping), and magnitude (e.g. Ahn and Griffin, 2008; Shanahan, 2004). Matsumoto and Griffin (2002) reported that the phase between two frequency components of an impulsive sinusoidal motion, as well as the phase between the subjective response and the motion, could also have an effect on relative discomfort. It was also observed that the natural frequency of the body varied with shock magnitude. The factors above may suggest that the motion to sensation relation for shock differs from that for continuous vibration.

Recent studies investigating biodynamic nonlinearity using continuous excitations have suggested that a shear-history dependence governed by the passive thixotropy of human soft tissues contributes to the biodynamic nonlinearity (i.e. Huang and Griffin, 2008a, 2008b, 2009). Lakie (1986) used the term thixotropy to describe a recovery of stiffness of relaxed index fingers subjected to an impulsive tap. The nature of thixotropy in this context was that the stiffness of body tissue reduces during and immediately after high magnitudes of excitation, while the stiffness increases during and immediately after rest or low magnitudes of excitation. The degree of reduction in stiffness is dependent on the displacement magnitude.

Constitutive descriptions of human soft tissues have assisted finite element analysis of local physical responses to vibration, such as those in fingertips (e.g. Wu *et al*., 2007) and buttocks tissues of seated persons (e.g. Verver *et al*., 2004; Siefert *et al*., 2006). However, these finite element models do not represent the ‘macro’ nonlinear softening effect observed in the frequency domain. This gap between the macro- and the micro-structure impedes the implementation of the nonlinear mechanism in biodynamic models of human dynamic response.

This paper aims to summarise evidence from human perception and biomechanical studies relating the nonlinear magnitude dependence of human discomfort and nonlinearity in objective measurements primarily caused by soft tissue. Studies are compared in two categories: i) subjective perception studies of whole-body vibration and mechanical shock; ii) experimental and analytical investigations examining dynamic properties of soft human tissue.

2. Perception studies

The majority of the studies reviewed below employed the method of magnitude estimation to determine the relative discomfort between a reference motion and a test motion. The magnitude of discomfort assigned to a reference motion was 100. Subjects were asked to estimate the discomfort of the test motion relative to the discomfort of the reference motion by assigning a value. For instance, subjects should give a value of 50 if the test motion is considered half as uncomfortable as the reference motion and a value of 200 if the test motion is considered twice as uncomfortable as the reference motion. The method of magnitude estimation is usually used when independent variables of interest are known in advance, for example, the effect of excitation frequency on the growth of discomfort with increasing excitation magnitude. If a large number of independent variables are of interest, or it is not known in advance which ones are of interest, or if an order effect of two paired motion is of interest, a paired comparison method is usually used (e.g. Howarth and Griffin, 1991; Matsumoto and Griffin, 2002).

The relation between objective and subjective magnitude can be used to construct equivalent comfort contours describing the frequency dependence of discomfort. This results in a series of frequency weightings presented in ISO 2631-1 (ISO, 1997) and BS 6841 (BSI, 1987).

Stevens' power function, $\psi = k\varphi^n$, is often used to express the relation between the objective magnitude φ and the subjective magnitude of perception ψ (Stevens, 1975). The exponent (n) denotes the gradient of subjective magnitude as a function of objective magnitude. The rate of growth in subjective magnitude with increasing objective magnitude is described by the exponent – an exponent higher than 1 indicates an increased rate of growth in the subjective magnitude. Recent studies reporting equivalent discomfort contours showed that the shape of the frequency-dependent contour changes with varying objective magnitude (e.g. Morioka and Griffin, 2006).

Six studies investigating the effect of excitation magnitude of whole-body vibration and mechanical shocks are reviewed in this section. The experimental conditions and methods are compared in Tables 1A and 1B and the objectives and main findings are summarised below.

Table 1A Perception studies: comparison of experimental conditions and methods.

Authors	Subjects, direction	Excitation, conditions, methods
HVCH-MJG 1991 EXP1	16 men Z-axis	SDOF oscillator in response to a unit displacement step input; natural frequencies = 1, 4, 16 Hz; damping ratio = 0.125, 0.250, 0.707; vertical upward and downward; VDV = 0.6, 1.0, 1.6, 2.5, 4.0 ms$^{-1.75}$. Comfortable upright sitting posture, thighs horizontal, lower legs vertical, feet flat on vibrator, rigid seat. Method of magnitude estimation, Stevens' function, reference: 4 Hz, 1.6 ms$^{-1.75}$, damping ratio 0.250.
EXP2	16 men Z-axis	1, 2, 4, 8, 16 repeated recorded shocks with VDV ($\int_0^T\{a(t)^4dt\}^{1/4}$) = 3.3 ms$^{-1.75}$ or second power dose ($\int_0^T\{a(t)^2dt\}^{1/2}$) = 2.6 ms$^{-1.5}$ overlapped by 34.2-s, 0.2-ms^{-2} r.m.s., octave bandwidth centred at 2 Hz continuous vibration, a(t) is the W_b weighted acceleration (BSI, 1987). The same posture as above but with a hard flat backrest. Paired comparison: subject indicated which was most uncomfortable, one scale value for each stimulus. Z-axis unweighted acceleration at seat evaluated using fourth power dose VDV (ms$^{-1.75}$) and second power dose (ms$^{-1.5}$).
YM-MJG 2002	Total 20, 10 men, 10 women Z-axis	Effect of phase: sinusoidal stationary vibration at 3 and 9 Hz, each having 1.0 ms^{-2} peak, the second component (9 Hz) was delayed by 0, 60, 120, 180 degrees, duration = 20 cycles of 3 Hz base motion; sinusoidal transient shock at 3 and 12 Hz, each having 1.0 ms^{-2} peak, the second component (12 Hz) was delayed by 0, 0.1, 0.2, 0.3, 0.4, 0.5 (0 = two components begin simultaneously, 0.5 = peaks of two components occur simultaneously), duration = 1.5 cycles of 3 Hz base motion. Effect of magnitude: sinusoidal stationary vibration at 3 and 9 Hz, each having 1.0 ms^{-2} peak, the second component (9 Hz) was delayed by 180 degrees, at five magnitudes of 1.60, 1.70, 1.80, 1.91, 2.02 ms$^{-1.75}$; sinusoidal transient shock at 3 and 12 Hz, each having 1.0 ms^{-2} peak, the second component (12 Hz) was delayed by 0.5, at five magnitudes of 0.600, 0.636, 0.674, 0.715, 0.757 ms$^{-1.75}$. Comfortable upright sitting posture, hands on laps, no backrest, feet hung freely, no distant external view, rigid seat. Paired comparison: modified Scheffe's method to construct a relative discomfort score from a discomfort judgement scale (-3, -2, -1, 0, +1, +2, +3). Z-axis acceleration at seat evaluated using r.m.s. (ms^{-2}) and VDV (ms$^{-1.75}$) when unweighted, and with w_k, w_b, apparent mass filter weighted.
YM-MJG 2005	12 men Z-axis	Sinusoidal continuous vibration: 3.15, 4.0, 5.0, 6.3, 8.0 Hz with each at 0.5, 1.0, 2.0 ms^{-2} r.m.s., duration = 4s for each motion. Sinusoidal transient motion: same frequencies as continuous with each lasting for 1.5 cycles with peak accelerations at -0.7, -1.4, -2.8 ms^{-2} r.m.s. Subjects sat on a horizontal flat rigid seat on the shaker, no backrest, feet on stationary footrest. Method of magnitude estimation, reference: 5 Hz and the same r.m.s. acceleration for continuous and the same nominal peak acceleration for transient. Z-axis unweighted acceleration and dynamic force at the seat-subject interface: apparent mass ratio, mechanical impedance ratio, normalized at 5 Hz, for both continuous and transient.
MM-MJG 2006	Total 36 12 men X, 12 men Y, 12 men Z	Sinusoidal vibration with 2 s duration at 23 preferred one-third octave centre frequencies between 2 and 315 Hz. Magnitude varied in velocity from 0.02 to 1.25 ms^{-1} r.m.s. in 3 dB steps. The magnitude varied between axes to cover the absolute perception threshold. Comfortable upright sitting posture, hands on stationary handles, feet on stationary footrests, thighs horizontal and level with seat, forearms horizontal and level with handles. Method of magnitude estimation (reference: 20 Hz 0.5 ms^{-2} r.m.s. in vertical, 20 Hz 1.0 ms^{-2} r.m.s. in fore-and-aft and lateral) and Stevens' function were used to establish equivalent comfort contours.

Notations: HVCH-MJG = Howarth, H.V.C. and Griffin, M.J.; YM-MJG = Matsumoto, Y. and Griffin, M.J.; MM-MJG = Morioka, M. and Griffin, M.J.

Direction: X-axis = fore-and-aft, Y-axis = lateral, Z-axis = vertical direction relative to the seated human body.

Table 1B Perception studies: comparison of experimental conditions and methods (continued).

Authors	Subjects, direction	Excitation, conditions, methods
SJA-MJG 2008	15 men Z-axis	Impulsive response of a SDOF model to a Hanning-windowed half sine force: 16 fundamental frequencies at preferred one-third octave centre frequencies from 0.5 to 16.0 Hz, each at five unweighted VDV of 1.7^{-2}, 1.7^{-1}, 1.0, 1.7, 1.7^{2} $ms^{-1.75}$, each at five damping ratios of 0.05, 0.1, 0.2, 0.4. Comfortable upright sitting posture, thighs horizontal on flat rigid seat, lower legs vertical, hands on laps, feet on shaker, no backrest, with hearing protector and eye mask. Method of magnitude estimation, Stevens' function, reference: 2.5 Hz shock, damping ratio 0.1, unweighted VDV 1.0 $ms^{-1.75}$ (3.1 ms^{-2} peak-to-peak). Vertical unweighted acceleration a(t) was evaluated with: peak-to-peak values, VDV ($\int_0^T\{a(t)^4dt\}^{1/4}$), second power dose ($\int_0^T\{a(t)^2dt\}^{1/2}$).
GHMJS *et al* 2009	12 men X-axis Y-axis	Sinusoidal vibration: 1.6, 2.0, 2.5, 3.15, 4.0, 5.0, 6.3, 8.0, 10.0 Hz with each at 0.125, 0.25, 0.5, 1.0 ms^{-2} r.m.s., duration = 4s for each motion. Subjects sat on a horizontal flat rigid seat on the shaker, no backrest, feet on stationary footrest. Method of magnitude estimation, reference: 4 Hz at the same acceleration magnitude of test motion. X- and Y-axis unweighted accelerations and dynamic forces at the seat-subject interface: apparent mass ratio, normalized at 4 Hz.

Notations: SJA-MJG = Ahn, S.-J. and Griffin, M.J.; GHMJS *et al* = Subashi, G.H.M.J. *et al*.

Direction: X-axis = fore-and-aft, Y-axis = lateral, Z-axis = vertical direction relative to the seated human body.

2.1 Howarth and Griffin, 1991

The first experiment was designed to investigate effect of shock frequency, duration and direction on the growth of discomfort with increasing magnitude of single shocks. The authors reported no significant effect of the above variables, suggesting that the growth of discomfort was independent of shock magnitude measured in the fourth power does (VDV). At constant averaged excitation magnitude in terms of the VDV, the greatest discomfort caused by the mechanical shock was found at 1 Hz, possibly caused by increased subjective judgements due to the greater visual impact of the motion displacement at 1 Hz as compared to 4 Hz and 16 Hz. Increased discomfort was found with decreasing damping ratio at constant VDV with the effect most apparent at 1 Hz.

With increasing number of shocks but constant averaged magnitude of excitation, using either second power dose or the VDV, the second experiment compared the accuracy of the two methods. The vibration dose value was found to be more accurate than the second power dose in predicting the reduction in shock magnitude required to counteract the increased discomfort associated with the greater number of shocks.

2.2 Matsumoto and Griffin, 2002

Subjective judgments of discomfort produced by sinusoidal continuous and sinusoidal shock motions were used to determine the maximum effect of phase at a range of excitation magnitudes. The relative phase of two frequency components within a stimulus, and the phase difference between the human subjective response and input stimuli represented by frequency weightings were investigated.

The results suggested that differences in the magnitude of the continuous vibration could be more easily detected by subjects than the shock motion.

For continuous vibration, different phases between two frequency components in the stimuli did not produce statistically different discomfort, but a 180 degree phase delay tended to produce less discomfort comparing with a zero phase difference.

For shocks, the results tended to suggest that the number of shocks perceived by subjects was a significant factor for judging discomfort. The authors demonstrated analytically that the phase response of a subject effectively reduced the time lag between two frequency components in the shock so making it more difficult for the separate shocks to be detected. The suggestion that human subjects might be more tolerant of a higher magnitude single shock compared to lower magnitude multiple shocks is contrary to current assessment methods and should be investigated further.

2.3 Matsumoto and Griffin, 2005

The study was designed to investigate the effect of excitation magnitude on the subjective and objective (apparent mass and mechanical impedance) responses for both sinusoidal continuous and sinusoidal shock motions.

For continuous vibration the authors attributed the significant increase in relative discomfort with increasing vibration magnitude at 3.15 and 4.0 Hz and the lack of a significant difference at 5 to 8 Hz, to the nonlinear biodynamic response. Over the range of magnitudes and frequencies investigated, the authors found the discomfort was slightly better correlated to mechanical impedance than apparent mass. A correlation between discomfort and mechanical impedance or apparent mass was found only at frequencies below about 5 Hz where inertial forces were relatively high. The correlation was less at higher frequencies as local body motions would not affect the inertial forces as much as at lower frequencies.

For transient motions, the discomfort was more highly correlated to mechanical impedance than apparent mass and, as with continuous vibration, stronger correlations between the subjective and objective responses were found at lower frequencies.

The authors suggested that the strongly nonlinear characteristics of the subjective responses could be caused by the similar nonlinearities in the driving point dynamic response.

2.4 Morioka and Griffin, 2006

The second of the two experiments investigating the effect of vibration magnitude on equivalent comfort contour was reviewed. The magnitude ranged from the perception threshold to levels thought to associate with discomfort and risks to health. The first experiment, which determined the thresholds, was not reviewed. In the second experiment, it was hypothesized that frequency dependence of relative discomfort (the equivalent comfort contour) would vary with vibration magnitude.

The frequency dependence of the equivalent comfort contours showed the strongest sensation to acceleration at between 5 and 10 Hz with vertical vibration, and at around 2 Hz with fore-and-aft and lateral vibration. These frequencies coincide with the principal resonance frequencies of the body.

The growth of sensation indicated by the exponent of Stevens' power function was the greatest for fore-and-aft and vertical vibration around the principal resonance frequency of the body (e.g. 2 to 5 Hz). The frequency dependence of the growth of sensation implied a magnitude dependence of the relative discomfort. The authors concluded that with increasing vibration magnitude, the equivalent comfort contours approximate to contours of constant velocity with 2 to 315 Hz fore-and-aft and lateral vibration, and with 16 to 315 vertical vibration. This change with vibration magnitude is consistent with the reduction in resonance frequencies of transmissibilities and apparent mass with increasing magnitude of whole-body vibration. The authors pointed out that no single linear frequency weighting could provide accurate predictions of discomfort and risks to health.

2.5 Ahn and Griffin, 2008

The study examined subjective responses to a series of vertical shocks with differences in fundamental frequency (natural frequency of the SDOF model), magnitude, decay rate (damping ratio), and direction (upward or downward).

The rate of growth in discomfort caused by shock motions decreased with increasing fundamental shock frequency, so the shapes of the equivalent comfort contours depended on the shock magnitude. At VDV magnitudes higher than 0.35 $ms^{-1.75}$, the frequency weighting W_b (BSI, 1987) tended to underestimate the discomfort caused by shocks at fundamental frequencies lower than about 2 Hz.

There was a tendency for the upper body to detect the discomfort from shocks with lower fundamental frequencies or higher magnitudes in the frequency range 0.5 to 1.25 Hz. The lower body became more sensitive to shocks with higher fundamental frequencies or lower magnitudes in the frequency range 6.3 to 16.0 Hz.

2.6 Subashi et al., 2009

The study investigated effects of frequency and magnitude of excitation on relations between subjective and objective responses of the human body during fore-and-aft and lateral whole-body vibration. It was hypothesized that the magnitude-dependent nonlinear change in relative discomfort was related to the biodynamic nonlinearity in apparent mass measured at the same time.

Peak frequencies of relative discomfort were around 2.5 Hz for both directions of excitation – similar to peak frequencies of apparent mass found with the same sinusoidal excitation, i.e. 2.5 Hz for fore-and-aft and 2.0 Hz for lateral vibration. Based on previous biodynamic studies in the horizontal and vertical direction of body movement and apparent mass (e.g. Fairley and Griffin, 1990; Kitazaki and Griffin, 1997), the authors speculated that the main body modes at these frequencies were caused by shear deformation of buttock tissue, and rocking and bending of the upper body.

With fore-and-aft vibration, positive correlations were found between median relative subjective discomfort and median normalized apparent mass with varying magnitude at 2.0 to 5.0 Hz. The author attributed the cause of the similarities in response to proportional increments in relative discomfort to increments in motion of body segments relative to the seat. Similar, but less clear, nonlinearities caused by vibration-magnitude-varying discomfort and apparent mass were found with lateral vibration.

The authors commented that discomfort was associated with apparent mass at lower frequencies (i.e. less than 5 Hz) where motions of the upper body dominated both directions, while at higher frequencies, where local motions at certain body parts dominated discomfort, subjective responses were unlikely to be related to the apparent mass of the entire body.

3. Soft tissues

The behaviour of the relaxed supine human body is typical of thixotropy when exposed to motions of abrupt intermittent change in magnitude, between 1.0 and 0.25 ms^{-2} r.m.s., for both vertical and longitudinal horizontal directions (Huang and Griffin, 2008a, 2008b). The stiffness as indicated by the resonance frequency of the body with a 0.25 ms^{-2} r.m.s. vibration immediately after 1.0 ms^{-2} r.m.s. vibration was lower than the stiffness during 0.25 ms^{-2} r.m.s. continuous vibration; the stiffness with 1.0 ms^{-2} r.m.s. vibration immediately after 0.25 ms^{-2} r.m.s. vibration was higher than the stiffness during 1.0 ms^{-2} r.m.s. continuous vibration. However, the effect was small, even with the reduced interference from muscular activity by using a relaxed supine posture. After 2.56 s of perturbation, the stiffness of the body recovered by about 90%. It was after about 30 s that the stiffness of human fingers subjected to an impulse tap recovered to about 80% (Lakie, 1986). It may be speculated that the difference in recovery time is because the tap of a finger can allow the whole extensor and flexor muscle to deflect so much so that the 'breakdown' of microstructures in the relaxed muscles and connective tissues is more thorough than that produced by internal movement of tissues involved in whole-body vibration.

If passive thixotropy of human tissue is the primary cause for the biodynamic nonlinearity seen in apparent mass and transmissibilities, it may also relate to the mechanistic causality for the subjective nonlinearity with varying excitation magnitude. Knowledge of the behaviour of soft human tissues varying with onset rate (or loading rate) and loading magnitude would improve the motion to sensation model.

Literature exists describing the dynamic mechanical properties of soft tissues, but with applications mainly restricted to time domain or extremely high strain rate (frequency) impact loading (e.g. Arbogast *et al*., 1997; Fung, 1993; Jindrich *et al*., 2003; Mavrilas *et al*., 2005; Snedeker *et al*., 2005). The two most relevant studies are reviewed here (Table 2).

Table 2 Soft human tissues: comparison of experimental conditions and methods.

Authors	Samples	Excitation, measures, results
HS *et al* 2007	Iced-fresh tissues of: Heart Stomach Liver Lung	Tested at 20°C room temperature immediate form thawing. Compressive bulk modulus – Kolsky bar (impact) – test: Tissue samples 12.7 mm in diameter, 1-2 mm thick. Confined compression at nominal strain rate 300 to 5000 s^{-1} (Strain rate $\varepsilon' = v / l_o$, where v = impact velocity; l_o = original length of specimen, a term similar to the onset rate of shocks). Duration of compressive pulse = 100×10^{-6} or 140×10^{-6} s. Bulk modulus of heart = 0.25 – 0.38 GPa (Bulk modulus is the ratio of applied pressure over volumetric strain – obtained by linear fitting), stomach 0.48 GPa. Shear (impact) test: Tissue samples 9x20 mm, 1-2 mm thick. Effect of shearing strain rate on shear modulus (i.e. shearing stress / shearing strain) – obtained by linear fitting, ε' ranges from about 200^{-1} to about 2800^{-1}. Shear modulus of heart = 60 – 148 kPa, stomach 8 – 45 kPa.
JZW *et al* 2007	Modelling of index fingertip	Finite element model (16 mm in width, 12 mm in height): Nonlinear elastic and viscoelastic: skin epidermis and dermis, subcutaneous tissue. Linear elastic: bone, nail, contact fingertip PVC support. Software, Abaqus standard v6.4. Pre-deformation in the normal to contact surface: 0.5, 1.0, 1.5, 2.0 mm Normal and tangential continuous harmonic vibration: 0.5 mm peak to peak, 16 to 2000 Hz octave bands Fingertip major resonance found at 100 – 125 Hz, secondary resonance at around 250 Hz in both normal vertical and tangential shearing directions. At low frequencies (around the major resonance), dynamic strain tended to penetrate into the tissue more than about 3 mm. at higher frequencies (around 1000 Hz), the depth was less than 1 mm.

Notations: HS *et al* = Saraf, H. *et al.*; JZW *et al* = Wu, J.Z. *et al.*

3.1 Saraf et al., 2007

The study provided an experimental basis for finite element modelling of dynamic compressive and shearing behaviours of soft human tissues, regarded as hyperelastic and viscoelastic. Hyperelastic (sometimes, nonlinear elastic) refers to variations in the force-displacement relation of a material without yielding, viscoelastic refers to variations in viscosity with changes in elasticity.

The dynamic compressive bulk modulus was approximated by linear regression between the applied pressure and resultant volumetric strain with no further demonstration of the effect of variation in strain rate. The dynamic shearing modulus was found to be of typical exponential form with low stress at low magnitudes of shear strain but exponentially higher stress as the strain increased. The heart and stomach tissues, both primarily consisting of muscles, exhibited considerable variations in response to different shearing strain rates but the variations were not quantified.

The authors pointed out in a supplementary document that explicit models were used to take into account the wave propagation in hyperelastic-viscoelastic shearing behaviour due to the time requirement for developing uniform stress state. The equivalent frequency and magnitude range (converted from the strain rate) used in the study were much higher than the range relevant to whole-body vibration studies. However, for mechanical shocks and prediction of injury, this range of data can provide a basis to quantify the physical responses of local tissues.

3.2 Wu et al., 2007

The study evaluated the frequency dependence of the dynamic strains in a fingertip model subjected to normal and tangential vibration.

The authors found shear vibration introduced considerable shear strain but little normal strain, but normal vibration introduced both normal and shear strain but the shear strain introduced by normal vibration was less than 0.3 mm.

At the single excitation magnitude investigated the motion transmitted into the tissues tended to decrease with increasing excitation frequency. The author commented that motion transmitted deep into the tissue, e.g. 1-3 mm, at low frequencies may cause damage to certain neural receptors, while at higher frequencies, e.g. >1000 Hz, there was potential for damage to local tissue.

4. Discussion and conclusions

The reviewed perception studies show a strong correlation between subjective sensation and measures of physical response of the body with varying excitation magnitude. If the passive thixotropy of soft tissues is a primary cause of the nonlinearity seen in the objective measures, it may also be related to the nonlinear characteristic in the subjective response. Current standards assume that the frequency dependence of relative discomfort is the same at varying magnitude. Mechanistic models based on thixotropic mechanisms may be able to improve predictions of subjective and objective response.

Human subjective and objective responses to shocks exhibit different characteristics with regard to continuous vibration. Current standards assume that the frequency dependence of relative discomfort is the same for both statistically stationary continuous vibration and mechanical shocks. This assumption tends to underestimate high magnitude discrete shocks at low frequencies (<2 Hz). Studies examining the mechanical properties of soft tissues may provide alternative measures for quantifying the nonlinear behaviour by using the strain rate, or loading rate, and defining the onset rate of motions transmitted to local tissue. The review also established that sensation, as well as physical damage, can be quantified by the instantaneous measures such as strain rate.

There has been a lack of knowledge on the physical responses of soft tissue to oscillatory motions at varying magnitude of excitation. This shortage may partly stem from a lack of established relationships between the measurable micro-structural properties (e.g. compressive bulk modulus and shear modulus) and macro behaviours (e.g. resonances in apparent mass and transmissibilities). The links between the two levels of behaviour have the potential to contribute to improvements in models of the nonlinearities in both physical and subjective responses of the human body to continuous and transient motions.

While standardised frequency weighting functions, and the magnitude-dependence of relative discomfort, as reviewed in the present paper all rely on the motion to sensation model to evaluate and assess risks to health, there has been no scientific evidence as to whether and how relative discomfort is associated with injury. The types of injuries may be different for different characteristics of excitation, in terms of strain rate and peak magnitude. The recent progress in the dynamic behaviour of soft human tissue and the mechanism of the biodynamic nonlinearity would improve modelling of body movement during continuous and transient abrupt motions and help identify the relationships between human responses and injury.

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