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VIBRATION TRANSMISSION THROUGH THE SHEEP PELVIS

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1. Introduction

Exposure to vibration in our modern society comes in many forms, ranging from mechanical shocks (e.g., automobile accidents and falls) to repetitive displacements of body parts occurring in the workplace (driving over-the-road vehicles) and during some forms of recreation (jogging). There is an extensive literature discussing the adverse physiological and subjective responses to vibration [1–3]. Symptoms range from mild discomfort and displeasure to debilitating and irreversible medical problems usually involving the spinal column [1]. Low back pain, resulting from a variety of workplace situations, including heavy lifting, use of jackhammers or machine tools, and operation of vehicles [4, 5] is the most common complaint among people exposed to whole-body vibration [6]. Low back pain is one of humanity's most disabling conditions[7], and has a significant economic impact on society [6], with costs annually in the United States estimated to be between $16 and $50 billion [4].

Most of the research involving occupational exposures to whole body vibration has been done on men [3]. Currently, there are no health or safety standards or gender-related corrections to existing standards regarding vibrational exposure in women. It is unknown whether or not these standards set for men would apply to women [8, 9]. Because the percentage of employed females of all ages in the United States has risen dramatically in recent years, from 43·3% in 1970 to 51·5% in 1980 and 56·6% in 1988 [10], and the fact that increasing numbers of women work in non-traditional jobs like truck, bus driving and heavy equipment operation, there is a need to determine the safe exposure levels for women. Naturally, as the total number of women in the workforce increases, so also does the cohort of potentially pregnant women. Among women whose first pregnancy occurred between 1981–1985, 64·5% worked during their pregnancy, and most of the women were working full-time [10]. Concerns arise, therefore, not only for the health and safety of working women in general, but for the embryo and fetus which many will carry for a significant time on the job.

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Prohibition against extensive whole body vibration investigations in humans has led to a search for a good animal model for these studies. Similarities in the mass of the abdominal contents of pregnant sheep make it a useful model for assessing side-to-side and front-to-back vibration transmission from the abdominal surface to the fetus [11]. Mechanical vibration of the abdominal wall resulted in a frequency related distribution of internal wall acceleration levels of 4% to 10% of the input levels [9]. At the fetal head, a broad peak in response was noted between 6 and 12 Hz. Pure tone vibrations (10 Hz) of the abdominal wall in non-pregnant sheep were found to produce intraabdominal iso-sound pressure contours that were fairly flat (in contrast to the decidedly curved contours developed during 2000 Hz vibrations) [12]. Vibration of the abdominal wall by electronic artificial laryngeal stimulators produces vibration levels at the fetal head proportional to high sound pressure levels within the uterus [13].

Because four parts of the bony pelvis (ischial tuberosities and lateral margins of the iliac crests) are close to the skin surface, the likelihood of abdominal segment vibration being introduced via a bony route is high. This paper explores the exposure across joints when bones rather than abdominal soft tissue are vibrated. A method is described for producing repetitive, direct mechanical displacements of the pelvis which produces acceleration levels at three locations in the bony pelvis of sheep.

2. METHODS

Guidelines for the care and use of the animals approved by the University of Florida were followed. Eight non-pregnant adult ewes weighing between 45–60 Kg were anesthetized with 2% halothane in oxygen by mask and intubated. The animals were placed prone on the operating table. The animals where shaved over the right iliac crests. That iliac crest was then exposed with the aid of a cautery. The periosteum and 2–3 mm of bone were removed in order to provide a flattened surface for contact with the actuator rod of an industrial shaker (Bruel and Kjaer Instruments [B & K], Naerum, Denmark, model 4808).

In 4 ewes two additional bony areas were exposed, the medial surface of the right iliac bone (hereafter referred to as ‘‘proximal’’) and the contralateral, left iliac crest (hereafter referred to as ‘‘distal’’). Miniature accelerometers (Endevco Corporation, San Juan Capistrano, CA, model 2222C) were fixed to these bony surfaces with cyanoacrylate ester. In 4 remaining ewes, miniature accelerometers (B & K, model 4501) were attached in a similar manner to the spinous process of the fifth lumbar vertebra. Both types of sensors (Endevco and B & K) feature high sensitivity to weight ratios, and internal resonances beyond the range of study. They were calibrated prior to each experiment with a B & K calibration excitor, model 4294, at 10 m/s^2. The photograph in Figure 1 shows B & K accelerometers fixed to the three positions described above (proximal and distal iliac crests and spinous process). B & K accelerometers were used in this photograph because their slightly larger size could be more easily visualized by the reader. The soft tissue and ligaments in and around the pelvis had been removed by Dermestidae beetles.

The actuator rod of a shaker, fitted with an impedance head (B & K, model 8001), was placed against the right iliac crest. The axis of vibration was in line with the axis of the accelerometers on the right iliac crest. The impedance head on the actuator rod was used to assure a constant input acceleration levels of 2·5 m/s^2 (r.m.s.) at the external surface of the right iliac crest for all stimulus frequencies.

The shaker was driven with sine waves generated with a Wavetek Signal Generator (San Diego, CA, model 182A) at the following frequencies: 5, 8, 10, 15, 22, 25, 20, 25, 30, 40, 60, 80, 100, 150, 250, 500, 1000, 1500, 2000, 5000 Hz. Spectral analysis was performed with a real-time analyzer (B & K, model 2123) in one-third octave bands over a range of 3·15 to 10 000 Hz. The dwell time was one minute. Analysis was performed on spectra for the stimulus frequency and at each of the three accelerometer locations, proximal iliac crest, distal iliac crest and spinal process of L-5. Spectra were stored on diskette and plotted on a graphics plotter (B & K, model 2319). Finally, the noise floor was obtained without stimulation and used to verify each response.

It was expected that vibration transmission would be significantly altered at the spinous process compared to the proximal or distal locations on the ilia. To test this hypothesis, a two-way repeated measures analysis of variance was used, with location (spinous/distal or spinous/proximal) considered as an 8-level within-subject factor. Due to the observed pattern of variation in which the standard deviation increased as the mean increases, responses were transformed logarithmically prior to analysis. The Bonferroni adjustment was used to maintain an experimentwise significance level of 0·05 for the comparison of spinous and distal mean and spinous and proximal mean responses at each frequency. The 95% confidence boundaries were also calculated for each frequency.

3. RESULTS

A constant vibration input (2500 mm/s^2 r.m.s., or 0·25 g) to the right iliac crest produced markedly different output responses for accelerometers positioned at both proximal and distal locations on the iliac crest and on a spinous process. These three output responses are illustrated in Figure 2. The most apparent feature of these responses is the frequency at which the peak level occurred. The resonant frequencies for the proximal location occurred at 1500 Hz. For the distal location the peak was seen at 500 Hz and for the spinous process the peak was at 100 Hz.

Results of the 2-way repeated measures ANOVA indicated that differences between spinous and distal means depended on measurement frequency ($p < 0{\cdot}0001$ for location $\times$ frequency interaction). The distal mean responses were significantly greater than the spinous mean responses at 500, 1000, and 2000 Hz, and the spinous mean

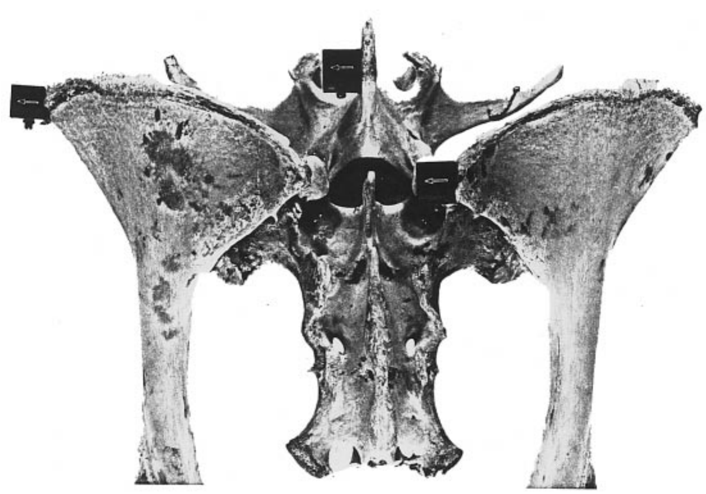

Figure 1. Photograph of the superior view of the pelvis of a non-pregnant sheep showing position of accelerometers on the right medial iliac crest, left lateral iliac crest and spinous process of lumbar 5 vertebra. Input vibration was through the right crest. Arrows indicate direction of vibration input.

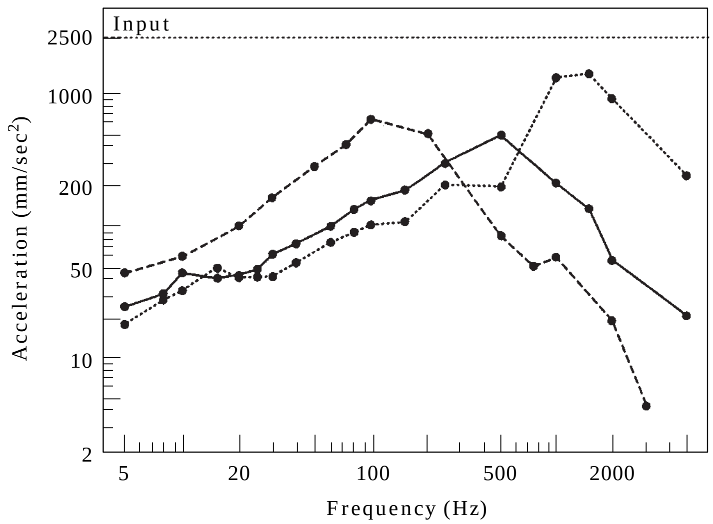

Figure 2. Relation between the level of acceleration at three bony positions and the frequency of sine wave input of 2500 mm/s^2 to the right iliac crest in anesthetized, prone sheep: ——, distal; . . . . , proximal; – – – , spinous process.

responses were significantly greater than distal mean responses at 20, 30 and 100 Hz ($p < 0{\cdot}05$).

Comparison of the spinous and proximal locations indicated that differences between means also depended on measurement frequency ($p < 0{\cdot}0001$ for the location × frequency interaction). The proximal mean response was significantly greater than the spinous mean response at 500, 1000, and 2000 Hz and spinous mean responses were significantly greater than proximal mean responses at 20, 30, and 100 Hz ($p < 0{\cdot}05$).

4. DISCUSSION

The concept of resonance is an important one, and it is frequently discussed in the literature on principles, measurements and health standards of occupational vibration [8]. Resonance, also termed ‘‘natural vibration frequency’’, means that the receiver is optimally tuned or coupled to the vibration sources, so that much of the vibration energy is amplified internally. When this occurs in human bodies, automobiles, bridges, crystal and other structures, there is structural weakening and even destruction. Prior to these end-points, humans may experience annoyance, discomfort and interference with activities including sleep [3].

While theoretical calculations and modelling of vibrating systems are one alternative to human experiments, animal experiments are useful too, especially when invasive procedures are required to obtain accurate data. The limitations of small animals, like rats or mice, for vibration experiments have been recognized [14], because of resonant frequencies, and thus maximum vulnerability, that are considerably higher than in larger mammals like humans. With appropriately anesthetized large animals, one can more easily study some factors that determine the vibration attenuation across bony joints as compared to small laboratory animals. Also, accelerometers can be placed directly on bones in question, thus avoiding any alteration in frequency response when transducers are required to be placed on the skin over the bone.

In the present study, the resonance of the medial aspect of the ipsilateral iliac bone was around 1000 to 2000 Hz. Qualitatively, the pelvic bones in these young adult ewes do not appear to be highly mineralized, and thus are not mechanically stiff, in comparison with adult human bones.

The marked shift in average resonance to lower frequencies (about 500 Hz) when the contralateral iliac crest was compared to the proximal iliac crest accelerometer position could be attributed to the interposition in the vibration path of the right and left iliosacral joints. Ligaments and other soft tissues lessen the stiffness of the conduction pathway and account for resonance peaks at lower frequencies. In terms of the response of the distal accelerometer, however, one cannot discount the bony fusion of the symphysis pubis in sheep which would form a mechanical conduction pathway across the abdominal segment. This conduction pathway would not be characteristic in women in whom the joint is more cartilagenous.

An even further shift to lower resonance frequencies to 100 Hz was found on the lumbar vertebra. This would be expected to occur because now the mechanical transmission pathway must traverse the iliosacral articulation and the articulation of the L5 and S1 vertebrae.

To what extent the vibration transmission across the iliosacral and symphysis pubis joints is changed during pregnancy by estrogens and relaxin remains to be determined, but it would almost certainly alter the biodynamic response, whether the vector is seat to head, as in most human conditions, or internally via the iliac crest.

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