Title

Vibration transmission of the spine during walking is different between the lumbar and thoracic regions in older adults

Abstract

Background: Fractures occur more commonly in the thoracic than in the lumbar spine. Physical activity complemented with pharmacological interventions has been advocated as a preventive measure for osteoporosis. However, walking has been shown to produce only a small improvement in spinal bone mineral density. The characteristics of vibration transmission during walking at the lumbar and thoracic spines may be different, and this may help explain the relative incidence of fractures in the two spine regions.

Objective: To determine how mechanical vibration is transmitted in the lumbar and thoracic spines in older adults with and without osteoporosis.

Methods: Sixteen young healthy adults, 19 older adults without osteoporosis and 41 adults with osteoporosis were recruited. Inertial sensors were attached to the skin over the lumbar and thoracic spines for recording the vibration transmitted during level walking. Vibration characteristics were compared across lumbar and thoracic spines and across groups.

Results: The lumbar spine generally amplified the vibration transmitted during walking, whereas the thoracic spine exhibited a much smaller amplification effect, except at the lowest frequency. The magnitude of vibration was generally reduced in the older spines. Osteoporosis had minimal effects on vibration transmission.

Conclusions: The larger amplification of vibration in the lumbar spine may explain the lower incidence of vertebral fractures in this region when compared to the thoracic spine. Ageing alters the transmission of vibration in the spine while osteoporosis has minimal effects. Future research should determine the characteristics of vibration transmitted through the thoracic spine during other physical activities.

Keywords

Walking, vibration transmission, osteoporosis, spine, ageing

Introduction

Vertebral fractures due to osteoporosis can have a significant impact on daily life activities since they can cause back pain, loss of height, deformity, immobility and reduced pulmonary function [1]. Current pharmacological interventions for the management of osteoporosis are limited due to their cost, side effects and issues associated with long term compliance [2]. It

has been suggested that physical activity may prevent osteoporosis and be used with pharmacological interventions [3]. Bone mineral density (BMD) improvements due to physical activity are only modest (<2% increment at the spine), site specific and have a greater effect on cortical than trabecular bone in contrast with pharmacological treatments [3, 4]. Walking has been found to produce limited improvement in spinal BMD or just to preserve it when performed along with other physical activities [2, 4, 5]. Studies related to physical activity in older adults often explore changes in metabolic and cardiovascular stress or changes in BMD and occasionally bone structure [2-4, 6, 7]. Currently there is limited understanding of the mechanical signals which are transmitted through the lumbar and thoracic spine during walking, although there is clear evidence that the processes of bone formation and resorption are responsive to mechanical factors [8].

Bone responds to mechanical stimulation in the form of vibration and the way this vibration is transmitted through the bone depends on its material and structural properties [9, 10]. Walking produces vibration that is transmitted through the body [11], thus its characterisation may help us understand the effects of walking on spinal bone metabolism. Unfortunately, it is not clear how osteoporosis and ageing may affect signal transmissibility. Vibration may be characterized by transmissibility as well as by the magnitude of the signal measured through inertial sensors attached to skin over the spine as validated previously [12]. Transmissibility is the ratio of the vibration measured between two points and is a function of frequency, when greater than 100% indicates amplification while attenuation is indicated by less than 100% [13]. Transmissibility through the spine has only been measured previously during walking in two young and healthy subjects [14, 15]. The thoracic spine is further away from the foot when compared to the lumbar spine, and it is therefore expected that the vibration signals in the two spine regions have different characteristics. In addition, there is uneven bone loss across the spine, and lumbar vertebrae are larger in size when compared with those at the thoracic spine [16]. Therefore it is important to study vibration transmission of the spine in both the lumbar and thoracic regions. These may be related to the differences in bone loss and fracture risk between the two regions.

The purpose of this study was to determine how mechanical vibration is transmitted in the lumbar and thoracic spines in older adults with and without osteoporosis.

Methods

Seventy six female participants were recruited and divided into three groups: young and healthy (age < 35 years old, YH, n=16, T-score > -1.0), older healthy (age > 55 years old, OH, n=19, T-score > -1.0) and older with osteopenia or osteoporosis (age > 55 years old, OO, n=41, T-score < -1). Further characteristics of the participants are compiled in Supplementary data

available in Appendix 1, *Age and Ageing* online. BMD was determined through Quantitative Ultrasound Scanning (QUS) (CUBAClinical®, McCue Plc.) [17]. Ethical Approval was given by University of Roehampton ethics committee (reference number SS10/021) and signed informed consent obtained. Exclusion criteria was: back or leg pain in the last 12 months that required medical treatment, severe rheumatological disorders, dislocation, fracture or surgery of the spine or lower limbs, neurological disorders affecting gait and a body mass index greater than 29 kg/m^2.

Four inertial sensors consisting of accelerometers and gyroscopes (Wireless InertiaCube3™, InterSens Inc.) were placed over the first sacral vertebra (S1) and over the twelfth (T12), eighth (T8) and first (T1) thoracic vertebrae. Sensors were aligned with the sagittal plane of the spine and attached to the participant's skin with double sided adhesive tape. Skin-sensor interfaces were subjected to "nudge" tests in order to correct for skin movement [12]. Participants walked 3 times at a self-selected, comfortable speed along a straight line of 33 m in length and 2 m wide. Vertical acceleration and dynamic sensor inclination were recorded throughout. Wireless timing gates (Smartspeed™, Fusion Sport Pty Ltd.) were used to calculate average walking speed.

The transmissibility and magnitude of the vibrations transmitted were determined using a previously validated protocol [12]. Transmissibility of vertical vibration along the spine was estimated as the ratio of the power spectral density (PSD) of the output (T12 for the lumbar spine and T1 for the thoracic spine) over the PSD of the input (S1 for the lumbar spine and T12 for the thoracic spine) and over the frequency range of 0.5 to 8 Hz. Mean maximum transmissibility (MMT) was determined at four frequency bands ($0.5 \leq f \leq 2$, $2 < f \leq 4$, $4 < f \leq 6$ and $6 < f \leq 8$ Hz) with 95% confidence intervals. Relative percentage difference in MMT between lumbar (x) and thoracic (y) spines was calculated by $((y - x)/|x|)100$ [18]. The magnitude of transmitted vibration was calculated as the root mean square of acceleration (RMSa).

Statistics were carried out using IBM®SPSS® (PASW Statistics 17.0, IBM Corp.). Transmissibility and RMSa were not normally distributed, as determined by Kolmogorov-Smirnov tests for each group. A non-parametric (Kruskal-Wallis) test was therefore employed to test the hypotheses that MMT (at each specified frequency bands) and RMSa were significantly different between groups (significance level of $P<0.05$). Post hoc tests were performed with a Bonferroni correction. The Mann-Whitney U test was used to test the hypothesis that RMSa and MMT at frequency bands are significantly different between lumbar and thoracic spines.

Results

Vibration transmissibility

Overall, the lumbar spine amplified vibration. The OO lumbar spine transmitted significantly more vibration (23% more, $P<0.05$) than the YH spine from 4 to 6 Hz. The older lumbar spines amplified vibration for all the frequency bands studied, and this was consistent irrespective of the presence of osteoporosis. MMT of the lumbar spine in the three groups was found to be frequency dependent, with the largest transmissibility from 6 to 8 Hz (Figure 1).

The thoracic spine exhibited a much smaller amplification effect when compared with the lumbar spine from 2 to 8 Hz. However at the lowest frequency band the thoracic spine presented a higher amplification when compared with the lumbar spine. The OH and OO thoracic spines transmitted significantly less vibration (30% and 24% less respectively, $P<0.05$) compared with the YH from 2 to 4 Hz. MMT of the thoracic spine, for the three groups, was found to be frequency dependent with largest transmissibility from 0.5 to 2 Hz (Figure 1).

Significant differences in MMT were found between YH and the two older groups but not between the OH and OO groups. No significant differences in MMT in any frequency band were seen between the OH and OO spines, suggesting that osteoporosis had little effect on transmissibility (Figure 1).

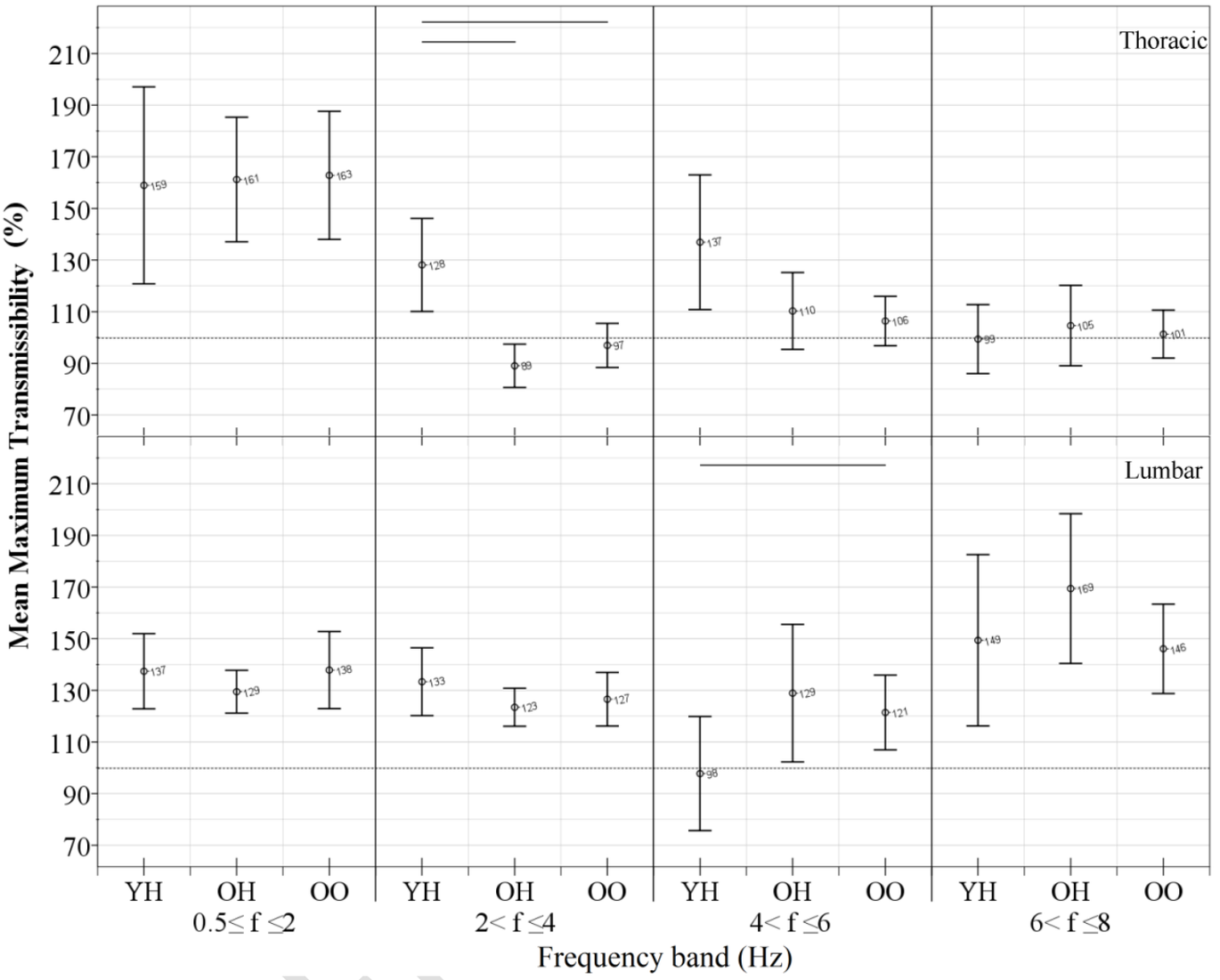

Figure 1 Mean maximum transmissibility of the lumbar and thoracic spines at frequency bands. ─ = significant difference between groups. Dotted line= 100% transmissibility, attenuation below and amplification above. Young and healthy (YH), older healthy (OH), older osteoporotic (OO). 95% error bars and mean presented.

Vibration magnitude

Reductions in mean RMSa were generally found at all anatomical locations in the two older groups when compared with the YH group, but there were no differences between OH and OO groups (Figure 2). However, when compared with the YH group, the OO group was associated with significant decreases in the mean RMSa at the sacrum and T1 ($P<0.05$) whereas the OH had significant decrease in the mean magnitude at T1 only ($P<0.05$).

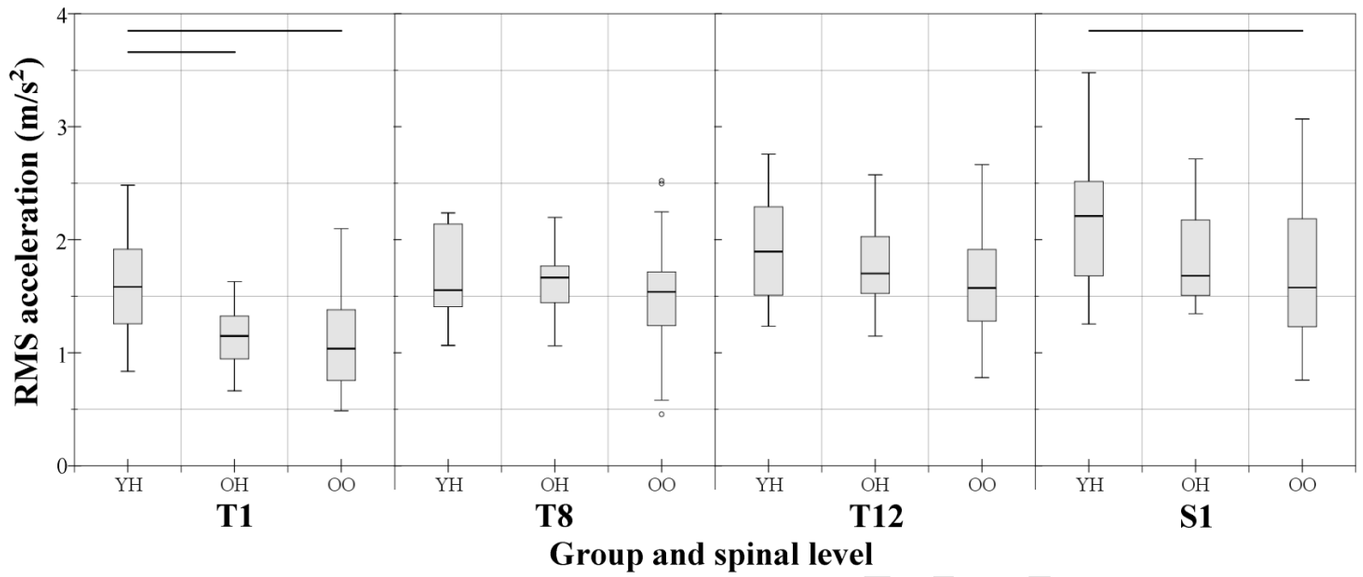

Figure 2 Root mean square (RMS) acceleration at first sacral vertebra (S1) and twelfth (T12), eighth (T8) and first thoracic vertebrae (T1). ― = significant difference between groups. Young and healthy (YH), older healthy (OH), older osteoporotic (OO)

Frequency differences in MMT between lumbar and thoracic spines

Since the concept of vibration transmissibility consists in three factors (percentage transmissibility, magnitude and frequency), here we present the percentage difference in MMT between the lumbar and thoracic spines at the various frequency bands (Figure 3). A positive percentage difference indicates larger transmissibility in the thoracic spine when compared to the lumbar and vice versa for a negative difference. Irrespective of the age and BMD of the subjects, the lumbar spine had a significantly larger transmissibility value when compared to the thoracic spine from 6 to 8 Hz ($P<0.05$). Age had an effect on the transmissibility difference between the two spinal regions as the older thoracic spines (OO and OH) transmitted less vibration (mean difference between 12% and 28%) from 2 to 4 Hz ($P<0.05$) and from 4 to 6 Hz. Conversely, the YH thoracic spine transmitted 40% more vibration ($P<0.05$) than the lumbar spine from 4 to 6 Hz. The OH thoracic spine transmitted 24% more vibration ($P<0.05$) than the lumbar spine from 0.5 to 2 Hz. These results show that ageing tends to lead to attenuation of signals in the thoracic region, although the response is frequency dependent.

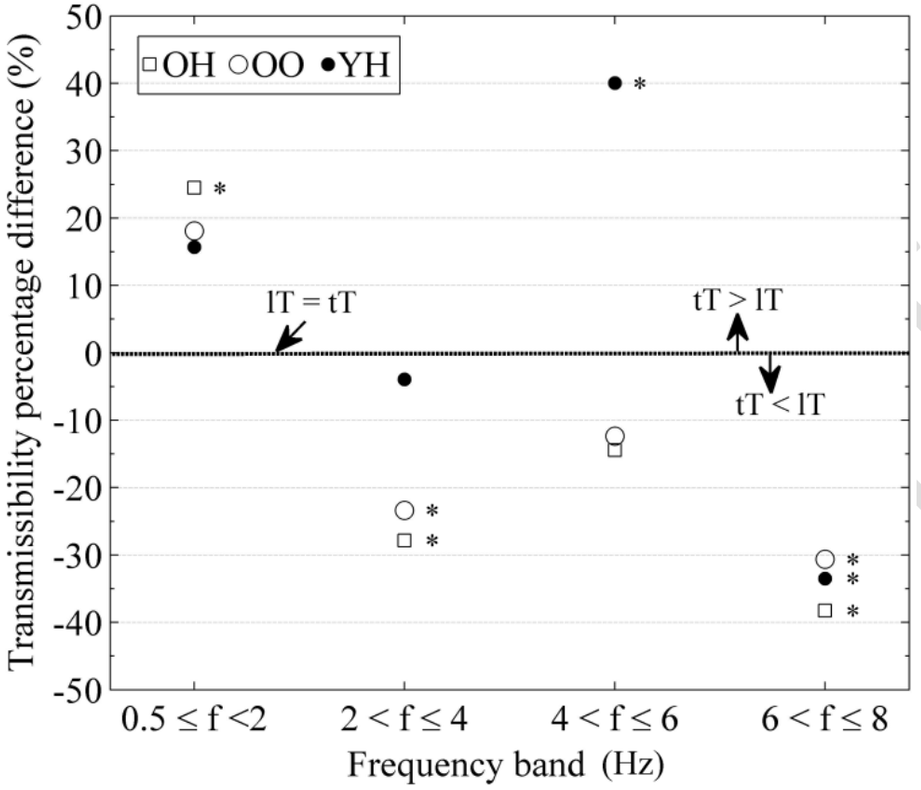

Figure 3 Percentage differences in mean maximum transmissibility (T) between thoracic (t) and lumbar spines (l) at various frequency bands. *=significant difference in T between l and t. Young and healthy (YH), older healthy (OH), older osteoporotic (OO)

Body height, walking speed and BMI were not significantly different between the three groups (P>0.05), subjects characteristics can be seen in Table 1 provided in the supplementary data.

Discussion

This was the first experimental study to examine how vibration signals are transmitted through the lumbar and thoracic spine during walking in older adults with or without osteoporosis compared to young healthy adults. The transmission of vibration is frequency dependent, and different between lumbar and thoracic spines. The lumbar spine generally amplified the vibration transmitted during walking, whereas the thoracic spine exhibited a much smaller amplification effect at frequencies higher than 2 Hz. Ageing appears to alter the transmissibility of vibration, and be related to both increment and decrement in the magnitude of vibration. However, osteoporosis has minimal effects on vibration transmission.

Vibration components of different frequencies and magnitudes travel at different speeds through the body, depending on the material properties of tissue, resulting in vibration storage, dissipation and distortion [19]. The overall mechanical properties

of the spine are determined by the size and shape of vertebrae and intervertebral discs and by the material properties, structure of soft tissue (cartilage, muscle, bone, tendons and ligaments) and the contractile state of the muscles. It is known that mechanical loads on the thoracic spine are modified by the rib cage, the thoracic kyphosis, the smaller thoracic vertebrae in comparison with lumbar vertebrae and the periodic body movement during walking [16, 20]. Biomechanical models have shown that the spine can support three times as much compressive loading when accounting for the rib cage compared to models excluding it [20]. Vibration may be transmitted through the rib cage reducing the load on the spine, hence the observed general reduced thoracic transmissibility in comparison with the lumbar region. In this study, we show that the older spines present significant changes in vibration transmission while the overall effects of osteoporosis in these spines are minimal.

Vertebral fractures occur most often at the thoracic spine and at the junction of thoracic and lumbar spines [21, 22]. The older thoracic spine is generally associated with less vibration amplification when compared to the lumbar spine. Osteoporosis has minimal effects on the vibration amplification of the thoracic spine. Clinically, this observed behaviour may either protect the spine from excessive signals or remove the mechanical stimulus necessary to stimulate bone in the thoracic region. We believe that the latter is more likely to be true as the incidence of osteoporosis is much higher in the thoracic region [1]. This may be a challenge for clinicians as to whether it is appropriate to mechanically stimulate these older spines or not in order to promote bone growth, as it is unclear if the extra stimulus may exacerbate current fractures or increase the risk of fractures. Further research is necessary to examine the potential physiological effects and clinical uses of increasing the stimulus delivered to the spine, for example, by increasing walking speed or by performing other types of physical activity.

The amplification of signal transmission seen in the lumbar spine may be due to the periodic movement of the trunk during walking and the associated muscle contraction required for maintaining balance and producing motion. Stronger muscle contraction has indicated that greater loads are exerted on the spine [23]. This increased muscle contraction may explain the increase in the dynamic stiffness of the trunk and thus its transmissibility increment seen in this study. Increased muscle contraction may be secondary to the loss of collagen in spine tissues during ageing [24]. Vibration transmission may also be amplified due to vertebral creep. Older adults may develop some degree of vertebral deformity due to bone creep [6]. In addition, vibration amplification was seen at the thoracic spine from 0.5 to 2 Hz in both older and young spines. This amplification may be related to the increase in stiffness as a result of active muscular contraction at low frequencies [25].

The measurement of RMSa has provided evidence that the older spines are generally receiving vibration magnitude which is smaller than that of the young spines. The magnitude of the vibration is consistently lower at the T1 level in the older spines (OO and OH) compared to the YH spines. This is likely to be the result of the observed older thoracic spine attenuating the vibration transmission, given that it transmitted between 10-40% less vibration (2-8 Hz) when compared with the older lumbar spine. Regarding the frequency at which vibration is transmitted, we observed that YH spines transmit significantly more vibration at the thoracic spine at 4-6 Hz, this is not the case for older spines. The implication of this effect on bone metabolism needs further investigation. These findings further reinforce the belief that ageing reduces the mechanical stimulus provided to the thoracic spine and may potentially increase the risk of thoracic fractures. It has been shown that dynamic loading from 0.5 to 2 Hz may produce an effective osteogenic effect [8]. This study clearly shows that walking produced the mechanical stimulation in this frequency range, but it is possible that the observed magnitude of that stimulus may not be sufficient to stimulate bone metabolism in the thoracic region. Indeed, a previous meta-analysis has revealed that walking exercise has little effect on the risk of vertebral fractures [26]. It is suggested that the relationship between RMSa dose, bone metabolism and the risk of vertebral fracture be further studied. Further research is necessary to determine the characteristics of vibration produced during other physical activities or therapeutic interventions and whether these will provide the required signals to the thoracic spine in order to stimulate bone metabolism.

Future research should examine the correlation between vibration transmissibility and volumetric bone strength. The current transmissibility method could be further used for objectively characterizing and identifying optimal physical activities to treat osteoporosis safely and effectively at various sections of the spine. For instance, it is necessary to know whether current prescription of physical activity for older adults can safely and effectively stimulate bone growth. In addition, it is possible that the performance of physical activity has an accumulative effect on the bone response.

Conclusion

Walking produces vibration that is significantly amplified by the lumbar spine but the amplification effect is much less in the thoracic spine. Even when greater amplification can be seen at low frequencies at the thoracic spine, the magnitude of that vibration is consistently reduced as it travels from the S1 to T1. Hence, the mechanical stimulation observed in the thoracic region may not be sufficient for maintaining bone health and this may explain the high incidence of vertebral fractures in this region. Ageing alters the transmission of vibration in the spine, but osteoporosis has minimal effects. The effects of ageing are frequency dependent and different in diverse spinal regions. The magnitude of the vibration transmitted by the spine during

walking is significantly decreased by a combination of ageing and osteoporosis, but only at the sacrum and at T1. Future research should examine the optimal dose of mechanical stimulus (in terms of the magnitude, frequency and percentage transmission of such vibration) required for stimulating bone growth and for preventing vertebral fractures. We suggest that prescribed physical activity as part of a healthy lifestyle or as a treatment of osteoporosis should consider the differences in the mechanical response between lumbar and thoracic spines. This mechanical response should account for both transmissibility and frequency components.

Key points

The thoracic spine exhibits a smaller vibration amplification compared to the lumbar spine during walking at frequencies above 2 Hz

The effects of ageing on spinal vibration transmission are different in different spine regions and frequency dependent

Spinal vibration transmission is significantly affected by ageing but not osteoporosis

Supplementary data

Supplementary data mentioned in the text is available to subscribers in Age and Ageing online.

References

1. IOF. *Data and Publications*. 2012 [cited 2016 13th October]; Available from: http://www.iofbonehealth.org/data-publications.
2. Hamilton, C., V. Swan, and S. Jamal, *The effects of exercise and physical activity participation on bone mass and geometry in postmenopausal women: a systematic review of pQCT studies*. Osteoporosis International, 2010. **21**(1): p. 11-23.
3. Gómez-Cabello, A., et al., *Effects of Training on Bone Mass in Older Adults: A Systematic Review*. Sports Medicine, 2012. **42**(4): p. 301-325.
4. Johnell, O. and J. Kanis, *An estimate of the worldwide prevalence and disability associated with osteoporotic fractures*. Osteoporosis International, 2006. **17**(12): p. 1726-1733.
5. Cheung, A.M. and L. Giangregorio, *Mechanical stimuli and bone health: what is the evidence?* Current Opinion in Rheumatology, 2012. **24**(5): p. 561-566.

6. Pollintine, P., et al., *Bone creep can cause progressive vertebral deformity.* Bone, 2009. **45**(3): p. 466-472.
7. Gueldner, S.H., *Osteoporosis: Clinical Guidelines for Prevention, Diagnosis and Management*, ed. S.H. Gueldner, et al. 2008, New York: Springer Publishing Company, LLC.
8. Skerry, T.M., *The response of bone to mechanical loading and disuse: Fundamental principles and influences on osteoblast/osteocyte homeostasis.* Archives of Biochemistry and Biophysics, 2008. **473**(2): p. 117-123.
9. Keller, T.S., C.J. Colloca, and A.W. Fuhr, *In vivo transient vibration assessment of the normal human thoracolumbar spine*. Journal of Manipulative and Physiological Therapeutics, 2000. **23**(8): p. 521-530.
10. Bhattacharya, A., et al., *Dynamic Bone Quality: A Noninvasive Measure of Bone's Biomechanical Property in Osteoporosis.* Journal of Clinical Densitometry, 2010. **13**(2): p. 228-236.
11. Cappozzo, A., *Low frequency self-generated vibration during ambulation in normal men.* Journal of Biomechanics, 1982. **15**(8): p. 599-609.
12. Morgado Ramírez, D.Z., S. Strike, and R.Y.W. Lee, *Measurement of transmission of vibration through the human spine using skin-mounted inertial sensors.* Medical Engineering & Physics, 2013. **35**(5): p. 690-695.
13. Mansfield, N.J., *Human Response to Vibration*. 2005, USA: CRC Press LLC.
14. Smeathers, J.E., *Measurement of transmissibility for the human spine during walking and running.* Clinical Biomechanics, 1989. **4**: p. 34-40.
15. Smeathers, J.E., *Transient vibrations caused by heel strike.* Proceedings of the Institution of Mechanical Engineers, Part H, Journal of Engineering in Medicine, 1989. **203**(4): p. 181-86.
16. Tortora, G.J. and S.R. Grabowski, *Principles of Anatomy and Physiology*. 10th ed. 2003: John Wiley & Sons, Inc.
17. WHO, *Assessment of fracture risk and its application to screening for postmenopausal osteoporosis. Report of a WHO Study Group*. World Health Organization Technical report series. Vol. 843. 1994, Geneva: World Health Organization.
18. Montgomery, D.C. and G.C. Runger, *Applied Statistics and Probability for Engineers*. Fith edition ed. 2011: John Wiley & Sons. 768.
19. Collins, J.J. and M.W. Whittle, *Impulsive forces during walking and their clinical implications.* Clinical Biomechanics, 1989. **4**(3): p. 179-187.
20. Andriacchi, T., et al., *A model for studies of mechanical interactions between the human spine and rib cage.* Journal of Biomechanics, 1974. **7**(6): p. 497-507.

21. Ravishankar, V., *Management of Osteoporotic Vertebral Compression Fractures: A Review.* American Journal of Clinical Medicine, 2009. **6**(4).

22. Waterloo, S., et al., *Prevalence of vertebral fractures in women and men in the population-based Tromso Study.* BMC Musculoskeletal Disorders, 2012. **13**(1): p. 3.

23. Izzo, R., et al., *Biomechanics of the spine. Part I: Spinal stability.* European Journal of Radiology, 2013. **82**(1): p. 118-126.

24. Shuster, S., *Osteoporosis, a unitary hypothesis of collagen loss in skin and bone.* Medical Hypotheses, 2005. **65**(3): p. 426-432.

25. Huang, Y. and M.J. Griffin, *Effect of voluntary periodic muscular activity on nonlinearity in the apparent mass of the seated human body during vertical random whole-body vibration.* Journal of Sound and Vibration, 2006. **298**(3): p. 824-840.

26. Martyn-St James, M. and S. Carroll, *Meta-analysis of walking for preservation of bone mineral density in postmenopausal women.* Bone, 2008. **43**(3): p. 521-531.