NEUROMOTOR TRANSMISSIBILITY OF HORIZONTAL SEATPAN VIBRATION

BY

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# 1 Abstract

Exposure to occupational whole body vibration (WBV) is associated with low back pain disorders, musculoskeletal disorders, and degeneration of spine. Transmission of vibration to the neuromotor system may play a role in the etiology of these injuries. Such WBV has components in the vertical, lateral and fore-aft directions. However, few studies have examined biodynamic vibration transmission in the fore-aft direction and no study has examined transmission of fore-aft vibration to the neuromotor system. The primary objective of this study was to assess the response characteristics of the fore-aft seatpan vibration. A secondary objective was to examine the effect of a backrest on these characteristics. Nineteen subjects participated in the study (10 male, 9 female, mean age $24 \pm 3$(SD) years, height $1.6 \pm .05$ m (SD), weight $69 \pm 7$ kg (SD)). The transmission of vibration to vibration-induced lumbar rotation (TF2) and paraspinal muscle activity (TF3), with and without the backrest, were quantified for a frequency range of 3-14 Hz at 1 RMS ($ms^{-2}$) and 2 RMS ($ms^{-2}$) vibration magnitudes. The mechanical transmission to lumbar rotations did not exhibit resonance within the measured frequency range without the backrest. The mechanical transmission with a backrest exhibited a ratio greater than one between 3-6 Hz indicating a resonance phenomena. Mechano-neuromotor transmission, the relationship between lumbar rotation and paraspinal muscle activity (TF4), without the backrest, exhibited a double peaked trend with a primary peak at 5-6 Hz and a secondary peak at 11 Hz. The primary peak at 5-6 Hz may be a result of coupled vertical motion and the 11 Hz might correspond to the internal resonance of the neuromuscular system. The small peaks at 6, 10 and 12 Hz for 1 RMS ($ms^{-2}$) and a larger

peak at 8 Hz for 2 RMS ($ms^{-2}$) were exhibited in TF4 with the backrest. The peaks at 6 and 8 Hz may be a result of coupled vertical motion or a result of external stimulating agent. The secondary peaks might be a result of internal resonance of the neuromuscular system. These results can be used in experiments examining the effects of fore-aft WBV on neuromotor habitation and muscular fatigue.

# 1.0 LOW BACK PAIN

Low back pain [LBP] is one among the most common disorders effecting about 70-80% of adults in their lifetime [1]. LBP is identified as one of the top three occupation-related, musculoskeletal disorders [2]. LBP is a leading cause of absenteeism from work, temporary disability, and workers compensation claims, with significant socioeconomic consequences [3]. It has emerged as the most expensive health care problem in the United States with reported annual costs ranging from $50 billion to $100 billion [4]. LBP is one of the leading causes of disability in the working population under the age of 45 [5-7].

LBP disability is growing 14 times faster than population [8]. One third of the American population is prone to low back pain disorders [9], which accounts for 33% of all workers compensation costs, making the medical costs in the diagnosis of LBP the highest. In the UK, workmen compensation benefits of more than 100 million days of sickness and disability are paid per year for incapacity due to LBP [10]. A study by the National Health Interview Survey [NHIS] in United States, reported 22.4 million cases of back pain in one year, which resulted in a total of about 149 million lost of work days [6].

Among the employees affected with chronic LBP, 50% of the employees did not return to work for 6 months and 75% remained off work for more than 1 year [11]. The costs of low back pain may be far greater in the future. 60% of people in Sweden on early retirement or long term sick leave claimed musculoskeletal problems as the reason [12]. In Germany chronic low back pain is one of the main reason for early retirement [13]. The total direct economic costs for use of health services that results from musculoskeletal conditions were 0.7% of the Gross National Product (GNP) in the

Netherlands, 1% in Canada, and 1.2% in USA. The indirect costs of musculoskeletal disorders were 2.4% of the GNP in Canada and 1.3% in USA [14, 15].

Regional differences, such as labor force participation rate and occupations, can contribute to the number of people suffering LBP across the world [16]. In industrialized nations, the lifetime prevalence of LBP is estimated to be about 60-80% [17, 18]. Low back pain affects men more than women, mainly because of the higher participation of men in physical labor [3]. Smoking, obesity, and negative social interaction, along with heavy manual work, twisting, lifting, prolonged driving, prolonged sitting, vibration, and unfavorable equipment interaction are considered to be the other factors that contribute to back pain [19]. A report by U.S. National Institute of Occupational Safety and Health (NIOSH) found the risk factors of WBV and manual materials handling to have a particularly strong association with LBP [20] [21].

## 1.1 Low back pain and exposure to whole body vibration

Driving vehicles and operating power tools which involve vibration have been linked to increased reports of back pain [22]. Workers in vibration environments such as drivers of tractors, fork-lift trucks, and other off-road vehicles are more susceptible to back problems than workers who are not exposed to vibration [23]. 40% of bus drivers have experienced low back pain with increasing prevalence with age [24]. Christ and Dupius found that, of those with more than 700 tractor driving hours per year, 61% had pathologic changes of the spine; of those with 700-1200 hours, 68% were affected, and, of those with greater than 1200 driving hours, 94% were affected [25]. Epidemiological studies have indicated that long-term exposure to occupational WBV is associated with degeneration of the spine and with low back pain disorders [26-29]. Early degeneration of the lumbar spine system and herniated discs were the most frequently reported adverse effects in workers exposed to WBV [30]. Boshuizen et al. [31] observed a trend to higher risks for LBP disorders with exposure to higher magnitude of WBV.

WBV measured in most of the industrial vehicles exceeds the 8 hour action level of 0.5 $ms^{-2}$ and even the exposure limit value of 0.7 $ms^{-2}$, proposed by the European Union Directive for Physical Agents [29]. Vibration magnitude in this study was expressed in terms of vector sum of the frequency-weighted root mean square (R.M.S) acceleration. The reported values of vibration magnitude varied from 0.25 to 0.67 $ms^{-2}$ in cranes, 0.36 to 0.56 $ms^{-2}$ in busses, 0.35 to 1.75$ms^{-2}$ in tractors and 0.79 to 1.04 $ms^{-2}$ in fork-lift trucks and freight–container tractors. 79.5% of truck drivers had pathologic changes of the spine [32]. Driving occupations involve exposure to both WBV and other ergonomic risk factors such as poor sitting or static posture, non-neutral trunk movements, and heavy lifting or carrying activities [33-35]. Exposure of occupants to WBV in seated postures during professional driving are prone to higher risks of LBP and sciatica [33-35]. A review of the epidemiological literature estimated that people who sat in vibrating environment close to or exceeding the ISO exposure limit, place their musculoskeletal system at risk [36]. In the Netherlands, a detailed estimation showed that more than 400,000 drivers experience exposure to whole-body vibration [19]. Prolonged exposure to whole body vibration can be a predictive factor for specific back disorders.

International Standard ISO 2631 standardized vibration dose to assess the total severity of vibration on human health [37]. Vibration dose was defined as function of the frequency-weighted acceleration over specific period [37]. Mathematical representation of dose value was represented as the integral of the fourth power of frequency-weighted acceleration (a(t)) over the time period of exposure (T):

$$\textbf{Vibration dose value} = \int_{0}^{T} a^4(t)dt \qquad \textbf{Equation 1.1}$$

Several studies have estimated the effect of vibration magnitude and duration of exposure on vibration dose value and LBP prevalence. Manual handling and seat discomfort in truck drivers affect this dose-response relationship [38]. Among the identified occupational groups (crane operators, bus driving, tractor driving, helicopter pilots) helicopter pilots were found to have the strongest association between LBD and vibration dose [39].

## 1.2 Vibration induced mechanical creep

Visco-elastic properties of the disc allow the spine segment to undergo creep. The disc is hydrated due to an osmotic pressure gradient caused by the presence of proteoglycans with in its structure [40]. Kazarian et al. [41] reported that mechanical response is different in degenerated discs, which they found to have a reduced ability to absorb shocks. McGill and Brown [43] investigated the creep and recovery of the lumbar spine in healthy men and women. In that study, during 20 minutes of deep flexion, reported a creep behavior represented by an average increase of 5 degrees to 6 degrees in the lumbar flexion angle. Occupants exposed to whole body vibration have become shorter through the day [44]. Pope et al. [45] measured the spinal height using a transducer, mounted on the top of a slight backwards-tilting column. The change in height was recorded during six consecutive exposures of alternate 5 minutes whole body vibration and 5 minutes static sitting with a 20-minute rest times between exposures. The occupants were exposed to a 5 Hz frequency and with an intensity of 0.1g RMS ($ms^{-2}$) [46]. Larger height loss was significant when exposed to vibration than exposed to static sitting.

Creep can also affect the ligamentous tissues in the spine. Continual cyclic loading leads to cyclic flexion-extension of the lumbar spine, resulting in creep within the viscoelastic structures of the spine. Creep of the lumbar spine results in a laxity across the intervertebral joint, resulting in increased relative motion (i.e., intervertebral translations and rotations), which might lead to decrease in mechanical stability and increased potential for low back disorders [42]. Creep within the visco-elastic structures cause desensitization of the mechanoreceptors. Solomonow et al. [42] study shows that the mechanoreceptors response to the central nervous system decline exponentially as the structures continuously underwent creep. Cyclic loading for 50 minutes, with an intermediate rest period of 10 minutes, and a final 50 minutes of cyclic loading showed that creep was induced in the ligaments, discs and capsules of the spine [42].

## 1.3 Vibration induced muscular fatigue

Muscular fatigue has been suggested as mechanism for low back injury. Muscular fatigue can be assessed using electromyography (EMG). A shift in power spectrum towards lower frequencies and in the same time an increase in EMG amplitude is characteristic for muscle fatigue development [47-49]. The RMS value of the signal reflects the degree of involvement of the muscle, whereas the spectral composition reflects localized muscle fatigue [50]. Under prolonged static contraction there is a general increase in EMG amplitude and a shift in frequency spectrum from high to low frequencies [51]. Under several frequencies of vibration (1.8,4.0 and 6 Hz) some authors have found a shift in the median frequency of EMG, after 90 minutes of driving simulation [49]. However, an EMG study in helicopter pilots subjected to WBV for flight duration of 2 hours, did not exhibit significant lower median frequencies. Muscular fatigue has been suggested to cause a shift of loads to the ligamentous tissues which induced LBP [52]. Muscular fatigue might also alter dynamic stability of the spine increasing risk of injury [52].

## 1.4 Effect of vibration on proprioception

In our laboratory, loss in proprioception has been investigated as a possible mechanism for low back injury [53]. Proprioception is defined as the integration of signals by the central nervous system (CNS), from the internal peripheral sensory pathways of the body to initiate appropriate responses such as joint stability, posture control [54]. A vibration can induce proprioceptive activity from the muscle proprioceptors. Exposure to vibration of frequencies between 10 Hz and 120 Hz resulted in illusory movements and altered proprioception [54, 55]. This illusory sensation is the sensation that the muscles are lengthening, when they are actually not during vibration exposure. After the removal of vibration, the neuromotor circuits can become habituated to constant vibration exposure reducing the accuracy in performing a desired task [56, 57]. Wilson et al. [53] found a vibration effect on proprioception with vertical seatpan vibration of seated occupant exposed to 5 Hz, 0.223 RMS ($ms^{-2}$) for 20 minutes. Error in a reposition test indicated a loss of proprioception while sensing the trunk positon [53]. Wilson et al. [53] also assessed the effect of loss in proprioception (magnitude of threshold) on dynamic response using a computational model and the results indicated that loss in proprioception could lead to greater delays in muscle response that in turn could lead to loss of trunk stiffness and stability.

## 1.5 WBV transmissibility

WBV are transmitted to the seated occupants in working environments through a vibrating seatpan, vibrating backrest, or a vibrating handgrip. The most common exposures to vibration may occur on off-road vehicles, which include industrial vehicles and earth moving machinery. The response characteristics of occupants exposed to whole body vibration were investigated based on four different modes of transmission. Based on the different transfer functions several investigators assessed the transmissibility characteristics of, vibration induced trunk acceleration, vibration induced lumbar rotations, vibration induced EMG activity in the low back muscles, and response of erector spinae muscle group to vibration induced lumbar rotations (mechano neuromotor transmission). Transmissibility is defined as the ratio of measured output amplitude on the structure for given input excitation. Trunk acceleration transmissibility is measured by mounting accelerometer on the surface of the body and comparing that acceleration to the input acceleration. The transmissibility magnitude shows the fraction of the vibration that is transmitted to the seated occupants [37]. Several studies have focused extensively on the mechanical transmission of input vibration to different body segments in the vertical seat pan vibration, such as the transmission to head, shoulder, cervical vertebrae, thorax, hip [37]. The transmissibility depends on the frequency and direction of the input motion. The direction of vibration could be linear such as vertical, fore-and-aft, and lateral or rotational (roll, pitch and yaw). Several investigators have measured the response characteristics of the occupant's when exposed to vertical seatpan vibration in terms of transfer functions. These are elaborated in this section.

### 1.5.1 Vertical seatpan trunk acceleration transmissibility

Trunk acceleration transmissibility has been measured as the ratio of accelerations measured at different levels of spine to the input seat acceleration. Experimental studies have reported consistent trends for occupants exposed to vertical seatpan vibration. Based on the transmission functions, the resonance behavior of the vibrating human can be identified. Resonance frequency can be defined as the frequency at which an object will freely vibrate after it has been stuck mechanically. At resonance, transmissibility peaks, typically at a magnitude above one, decreasing with increasing frequencies. Between 4 Hz and 6 Hz, a pronounced principal resonance is exhibited in the seat to spine transmissibility [59, 60]. For vertical vibrations, the pitching motion of the pelvis can induce a flexion-extension motion of the lumbar spine [62]. This principal resonance might therefore be a combination of vertical motion of the entire body and flexion-extension motion of the spine [63]. A drop of about 2 amplitude decades per frequency decade is noticed above 6 Hz [37]. Sitting postures and the seat conditions can change the frequency of the principal resonance [59, 60, 64]. Different postures exhibit different modes of resonance behavior [23]. The natural frequency for principal resonance has been shown to increase to 5.2 Hz during erect posture, and to decrease to 4.4 Hz in slouching. During the principal resonance, a bending motion of the lumbar spine is exhibited which may stress or cause damage to structures of the low back. Pope et al. [64] observed that subjects experienced a significant gain at 5 Hz in the relaxed posture with an second attenuation peak of 7 Hz to 8.5 Hz. Sitting on soft cushions moved the resonance frequency to below 4 Hz, while stiffer padding of the seat increased the frequency of the transmissibility peak.

Griffin et al. [37] examined the response characteristics of seated occupants with a backrest that exhibited a single peak at 6.5 Hz. The seat, which had a short backrest, was used in this study. In this study the seated occupants were exposed to a random vibration at 0.2-16 Hz for 60 seconds at 1.75 $\pm 0.05$ RMS ($ms^{-2}$) [37]. The transmission characteristics of spine were measured using invasive and non-invasive techniques. To eliminate the skin motion artifact few studies have attached accelerometers directly to the spinous process invasively. A few studies measured the non-invasive spine measurement, which is discussed in detail in the following subsection.

#### 1.5.1.1 Non-invasive spine vibration measurement

Transmission of vibration to the human body involved measurement of bone motion at a desired location, on the spine. The use of skin-mounted accelerometers is the easiest and convenient non-invasive method of measuring the motion of the under lying bone. The instrument, when mounted on the skin can over estimate true spinal motion since direct contact with the vertebrae is not made. However bone mounted accelerometer, which is a better indication of bone acceleration, are not practical for in vivo cases. Bone mounted accelerometers measure the bone motion by inserting kirschner wires into the spine under local anesthesia. The usage of krischner wires requires proper medical skill and the measured data may vary depending on the thickness of wires and depth of insertion [65]. Several investigators have attempted to reduce or correct the effect of local-tissue on skin mounted accelerometers by preloading, mass preloading, spring preloading and strap preloading [66]. Preloading resulted in additional resonant systems, which in turn did not entirely eliminate the effect of skin artifact.

Hinz et al. [65] assumed a single degree of freedom linear model in both the vertical and fore-aft direction on the spine to examine skin mounted accelerometer vibration. The model consisted of one mass, a linear spring and a viscous damper. The accelerometer mounted represented the bone vibration through a spring and a viscous damper, which represented the skin effect [65] [Figure 1.1]. The equation of motion for the linear model system is.

$$\mathbf{m\,\ddot{x}_a(t)} + c(\mathbf{\dot{x}_a(t) - \dot{x}_t(t)}) + k(\mathbf{x_a(t) - x_t(t)}) = 0 \qquad \textbf{Equation 1.2}$$

Correction frequency function to eliminate the effect of local-tissue accelerometer is obtained by the inverse transfer function of the local system represented in equation 1.3.

$$T(\omega_n, \xi) = \sqrt{\frac{1 + (2\xi\omega/\omega_n)^2}{(1 - (\omega/\omega_n)^2)^2 + (2\xi\omega/\omega_n)^2}} \qquad \textbf{Equation 1.3}$$

with $\omega_n = 2\pi f_n = \sqrt{\frac{k}{m}}$ , $\xi = \frac{c}{2\sqrt{m\,k}}$ and $\delta = \frac{\omega}{\omega_n}$

Where T $(\omega_n, \xi)$ is a correction frequency function; $\xi$ is the damping ratio, $\delta$ the frequency ratio, and $\omega$ and $\omega_n$ are the excitation angular frequency and natural frequency respectively. The natural frequency and damping ratio were estimated from the free oscillation test. Accelerometers, which were attached to a stiff card, were mounted on the vertebrae L3 of the spinous process. Pulling the stiff card up or down and releasing it gently produced free oscillations. From the correction frequency function, and measurements from the skin-mounted accelerometers the acceleration to that of the bone was obtained from the following equation.

$$\mathbf{A_b} = T(\omega_n, \xi)^{-1} * \mathbf{A_s}$$ **Equation 1.4**

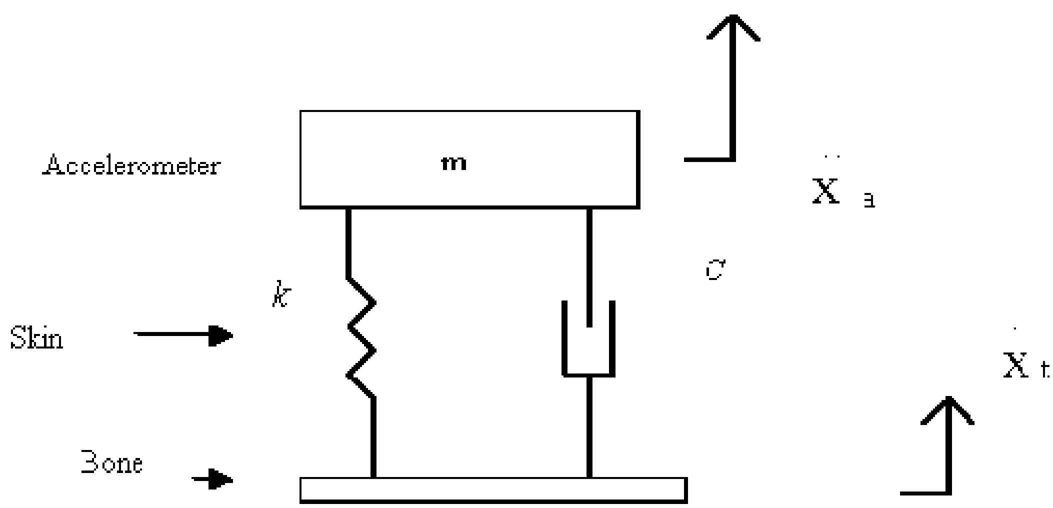


**Figure 1.1: Schematic of the mathematical model for the local system**

The estimated accelerations on the bone using the correction factor and accelerations measured on the skin, in the vertical direction exhibited a large change in magnitude when compared to the acceleration measured on the skin. The fore-and-aft acceleration response did not exhibit significant variations in acceleration measured on the bone when compared to the accelerations measured on skin suggesting correction factor is not necessary in the fore-aft movement.

### 1.5.2 WBV induced myoelectric activity

Whole body vibration is found to exhibit muscle activity in several studies [54]. Mechanical vibration applied to the seated humans, causes the low back muscles to exhibit electric activity. A muscle stretch will cause a contraction in the muscle spindles located inside the muscle. The muscle spindles contract so as to resume to its initial state is termed as stretch reflex [71]. Muscle spindle consists of intrafusal fibers (Nuclear bag and Nuclear chain fibers) and sensory nerve terminals, which provide information in positioning and movement. The intrafusal fibers can excite the neurons of the muscle spindle leading to a muscle contraction or reflex contraction [71]. These muscle contractions are initiated by an electrical impulse, which can be recorded using the technique of electromyography (EMG), which produces signals of varying sizes according to the intensity of the contraction. Vibrations applied to the muscle is subjected to numerous stretch cycles that cause the muscle spindle to fire in a one to one arrangement or a harmonic of the vibration frequency [55]. The effect of vibration to the muscles results in Tonic vibration reflex or a tonic contraction (position response), which is a repeated stretch reflex and a phasic activity (movement) [70]. Tonic muscle activity is considered critical for normal musculoskeletal function. Tonic represents the mean baseline of the EMG activity and phasic represents the peak-peak variation of EMG activity for a sinusoidal vibration input. It was also examined that muscle activity resulted from the lumbar rotation [69]

Several investigators measured the response of axial seat pan vibration interms of EMG. Abraham's study which included measure of peak-to-peak nEMG exhibited a peak at 4 Hz for 2 RMS ($ms^{-2}$) vibration magnitude and at 6 Hz for 1 RMS ($ms^{-2}$) and 1.5 RMS ($ms^{-2}$) magnitudes and a smaller peak was exhibited at 10 Hz [73]. Seroussi et al. [68] study also exhibited a peak between 4-6 Hz. A maximum peak-peak EMG between 4.5-6 Hz was also reported by Zimmerman et al. [70]. The response characteristics of these results indicates that the exhibited peak between 4-6 Hz frequencies range is a result of higher muscle activity required at those regions of trunk resonance to stabilize the upper body.

Time delay measured between the peak of acceleration and peak of muscle activity exhibited a drop in magnitude with increasing frequency [68, 73]. The time delays exhibited in different studies exhibited different trends. A drop in magnitude from 230 ms at 3 Hz to 150 ms at 10 Hz was estimated by seroussi [68]. Abraham [73] measured the time delay for a frequency range of 3 to 20 Hz and with 1,1.5 and 2 RMS ($ms^{-2}$) acceleration exhibited a drop from 230 ms at 3 Hz to 70 ms beyond 8 Hz. Among the measured time delays Abraham's study showed a steeper drop than that of seroussi.

### 1.5.3 Vibration induced lumbar rotation transmissibility

Vertical sinusoidal input to the seated occupant induces both vertical and angular motion of the lumbar spine [63]. In the vertical seat pan vibration spinal flexion corresponded to upward seat acceleration and spinal extension motion correspond to downward seat acceleration [68]. Cyclic flexion-extension motions of the lumbar spine have been observed to decrease with increasing frequency. Whole body vibration induced pelvic and back motion for frequencies of 4.5 to 16 Hz and with an intensity of 1RMS ($ms^{-2}$) exhibited greater pelvic motions at the principle resonance (i.e 4.5 Hz) of the human spine [70]. Torso and head rotation can be effected by subject posture and trunk stiffness. Pelvic and back motions for three different postures, neutral upright, and anterior and posterior pelvic tilt with respect to neutral were observed at frequencies of 6 Hz and lower [70]. Higher lumbar motion was noticed in postures where the trunk is posterior with respect to a neutral upright posture as compared to anterior trunk postures. Back rotations measured in the study exhibited smaller magnitude at 8 Hz that at 4.5 Hz. Abraham's study measured the vibration induced cyclic flexion-extension of the spine with a lumbar electrogoniometer mounted on the T-12 of the spinous process at frequencies of 3-20 Hz and magnitudes of 1-2 RMS ($ms^{-2}$) [73]. Vibration induced lumbar rotations measured in this study exhibited a peak at 4 Hz and a gradual decrease with increasing frequency at all vibration magnitudes. The greater pelvic motion observed at 4 Hz correlated with greater trunk acceleration transmissibility with the same principle resonance.

### 1.5.4 Mechano-neuromotor transmissibility

The vibration induced lumbar rotations transmission occurred within the neuromuscular system and is termed as neuromotor transmissibility. Mechano-Neuromotor-Transmissibility (MNT) is the ratio of vibration-induced EMG to that of the vibration induced lumbar rotations. Abraham [73] measured the response characteristics of the trunk muscle activation through reflex activation from lumbar rotations in the vertical seat pan vibration study [Figure 1.2]. The vibration-induced muscle activity through lumbar rotations exhibited a double peaked transmission mode at 4-6 Hz and 10 Hz in the axial seat pan movement. A constant transmission with increasing frequency exhibiting a peak at 4 Hz for 2 RMS ($ms^{-2}$) magnitude and a peak at 6 Hz for 1 & 1.5 RMS ($ms^{-2}$) respectively. A smaller peak was seen at 10 Hz. The peak at 4-6 Hz was found to be the effect of axial vibration or the effect of other feedback response loop such as voluntary control. The second peak at 10 Hz corresponded to the internal resonance of the neuromuscular system. In the simulink model developed by Abraham [73], the closed loop system response of a sinusoidal sweep for a 50 ms time delay, exhibited higher displacements at 10-12 Hz and hence the secondary peak in the mechano-neuromotor transmission is found to be a result of internal resonance in the neuromuscular system [73]. In a similar study by Abraham et al [88], estimated the response behavior of the transmission to the neuromotor system using a lumbar belt. The transmission patterns also exhibited a peaking behavior at 4 Hz and at higher frequencies with ‘belt-on’ the results were less effective in reducing the lumbar rotations at these frequencies. The study was investigated over a frequency range of 3-20 Hz and vibration magnitudes of 1 and 2 RMS ($ms^{-2}$).

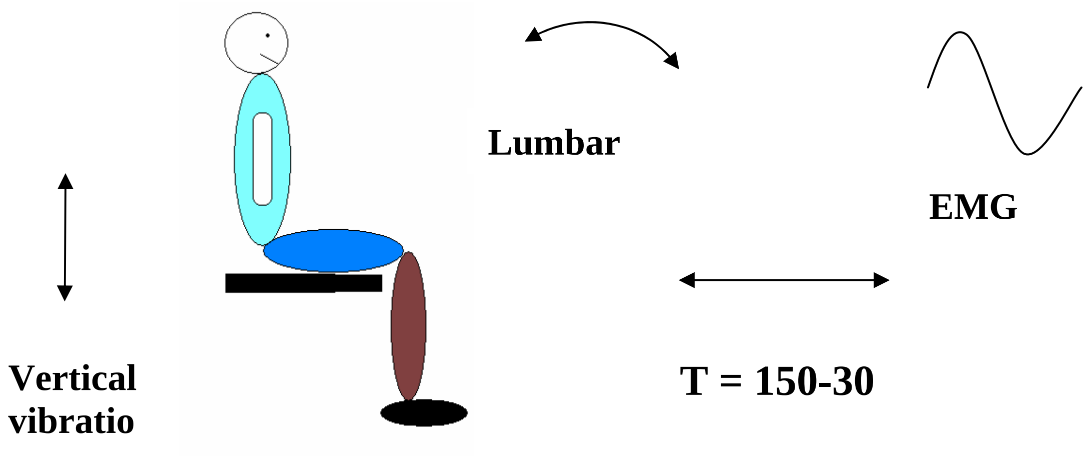


**Figure 1.2: Schematic of Mechano-Neuromotor transmission**

Time delay between vibration-induced back rotations and nEMG exhibited a gradual decline with increasing frequency. The signal transmits through neural pathway and arrive at the destined motor neurons to initiate appropriate responses [73]. The time required for the signal to transmit to the destined point is termed as delay [73]. nEMG lagged behind vibration-induced back rotations by 150 ms at 3 Hz to 30 ms at 20 Hz [73]. Stretch reflex is a result of vibration-induced lumbar rotation, which suggests a transition from more complex polysynaptic reflex and voluntary feedback systems that are associated with longer time delays to faster monosynaptic reflex feedback systems.

## 1.6 Lateral seat pan vibration transmission

Paddan et al. [76] measured the vibration response in the lateral (side-to-side) direction. The acceleration of the head was measured using an accelerometer mounted on a bite bar along the lateral direction. With a backrest condition the head moved mainly in the lateral direction. The response characteristics exhibited a resonance peak at a very low frequency of 1.5 Hz. The transmission function with the backrest (‘BACK-ON’) condition exhibited a very little effect when compared to other axis (fore-and-aft, vertical) of excitation. The measure of seat-to-head transmissibility without a backrest (BACK-OFF) in the lateral direction exhibited a slightly more head motion around 2 Hz. At very low frequencies and without a backrest (‘BACK-OFF’) condition the transmissibility values exhibited high values when compared to those of BACK-ON condition [76].

## 1.7 Horizontal (fore-and-aft) seat pan vibration transmission

While many studies have investigated the responses of seated human subjects exposed to vertical seat pan vibration in terms of mechanical transmissibility, the effect of horizontal (fore-and-aft) vibration has not been extensively investigated. Griffin et al. [76] measured the amount of fore-aft vibration transmission to the head with and without the effect of backrest. Measurement of seat-to-head transmissibility was investigated for several reasons including the role of the head in visual input. In addition, skin motion artifacts can be minimized in most frequency ranges through the use of a bite bar. The accelerations were measured to the head using a bite-bar while the occupants were exposed to fore-aft vibration. The subjects were exposed to random vibration at intensity of 1.75 $\pm$ 0.05 RMS ($ms^{-2}$) with two seating conditions (i.e. with and without a backrest conditions). The measured transmissibility curves exhibited a gradual decline with increasing frequency. The test was conducted in a frequency range of 0.2- 16 Hz [76]. The transmissibility curves exhibited a peak at 2 Hz with the backrest condition. The measure of transmissibility with the backrest condition exhibited a peak at 1.5 Hz and a secondary peak at 8Hz. The seat had a short backrest while the subjects were exposed to fore-and-aft vibration with a backrest. The resonance peak exhibited at 8Hz is solely due to the backrest contact.

Fairley et al. [77] assessed the response characteristics of seated occupants using apparent mass frequency functions in the fore-and-aft direction [77]. The apparent mass measure is a ratio of the horizontal force transmitted at the occupant and seat interface to the acceleration measured between the occupant and seat interface. The force plate platform mounted on the hydraulic shaker had a vertical backrest, which measures the total horizontal force both on the platform and the vertical backrest. The accelerations in the fore-aft direction were measured using two accelerometer mounted on the seat pan and backrest oriented in the fore-and-aft direction. The results without a backrest exhibited two resonance modes in the fore-and-aft direction, with a primary resonance peak at 0.7 Hz and a secondary resonance peak at 2.5 Hz. Only one resonance peak was exhibited at 3.5 Hz when a backrest was used. The study was conducted from 0.25 to 20 Hz with random vibration and at magnitudes of 0.5-2.0 RMS ($ms^{-2}$). These response characteristics were used to assess the dynamic interactions of the body with the seat pan and backrest [77].

## 1.8 Importance of horizontal (fore-and-aft) vibration

The majority of the studies assessing vibration transmission measured and analyzed the responses of seated human occupants to vertical vibration. However exposures to whole body vibration are rarely restricted to just vertical motion. Usually, there is some element of horizontal movement and in some circumstances the horizontal movement can dominant. For off-road tractors when ploughing, harrowing or drilling, the magnitudes of frequency-weighted horizontal vibration was found to be either comparable to or exceeding that of the vertical vibration [78, 80]. Vehicles such as articulated trucks, earth moving machinery, industrial vehicles such as excavators, off-road, forklift trucks, and port cranes exhibit large amounts of fore-and-aft seat vibration [37, 81]. Tractors and tanks have been shown to have more weighted acceleration in the horizontal directions than in the vertical direction. Fore-and-aft vibration of the backrest of a seat can cause appreciable vibration of the body [76]. It can also be a dominant cause of discomfort in some vehicles [82]. Among the 56 construction vehicles measured by Lundstrom et.al, for the multiaxis vibration magnitudes, 13 of the vehicles exhibited more weighted vibration in the horizontal or fore-aft direction and the remaining vehicles in the horizontal direction exhibited at least 90% of that reported for vertical motion [83]. Despite the known exposure to horizontal vibration in such vehicles, previous studies of vibration exposure and transmissibility have focused on the effects of vertical vibration on the human body.

In our laboratory recent research findings have suggested that vibration-induced neuromotor habituation occurs with the seatpan vibration so it is important to investigate transmission to the neuromotor system in all vibration directions [53]. Whole body seat pan vibration also induces both axial and rotational motion of the lumbar spine in the vertical seat pan vibration but this has not been studied for the fore-and-aft vibration [68]. It was also found that muscle activity corresponded with the lumbar rotation but this correspondence has not been examined for fore-and-aft vibrations [73]. The response characteristic of the human spine to fore-and-aft vibration requires the assessment of vibration frequency and amplitude on the transmission functions between, seat and low-back flexion-extension and neuromuscular system (low back flexion-extension motion and paraspinal muscle activity). Also the neuromotor responses in the fore-and-aft direction can further be used for better understanding of neuromotor habituations and its consequences such as low back stability in the fore-and-aft direction. Finally, Fairley et al. [77] found that large biodynamic interactions may occur with a backrest in the fore-and-aft vibration, which might result in altered motion of the spine. This interaction has not been studied for neuromotor transmission and should be investigated further.

## 1.9 Objectives and hypothesis

Although there have been studies on the biodynamic interaction of humans with the seat and the seat-to-head transmissibility with the fore-and-aft vibration there are no studies examining the response characteristics of the vibration-induced EMG and mechano-neuromotor transmission. The motion of the human lumbar spine needs to be assessed to better understand the transmission characteristics in the fore-and-aft vibration. The missing link between lumbar rotations and paraspinal muscle response, vibration-induced lumbar rotations, and vibration-induced muscle activity has to be better understood to assess the behavior of vibration in the fore-and-aft direction. The primary objective of this study was to measure the vibration response in terms of transfer functions equations 1.5-1.8, trunk acceleration transmissibility (TF1), the vibration transmitted to lumbar rotations (TF2), the vibration-induced muscle activity (TF3), and the transmissibility function between lumbar rotations and the paraspinal muscle response (TF4). The time delay between the peak occurrence of input to the peak occurrence of output and phase responses of TF3 and TF4 were investigated.

As many machines that expose drivers to WBV require the use of backrest, and WBV transmission is also influenced by back rests which also needs to be assessed [77, 80-83]. Hence the transmissibility functions (TF1-TF4) were measured with and without a backrest (i.e. BACK-ON & BACK-OFF) conditions. As the backrest provides support for the thoracic region it was hypothesized that backrest might stiffen the trunk and reduce cyclic lumbar flexion-extension motion. Based on the hypothesis, the backrest might reduce transmission of fore-and-aft seat pan vibration to lumbar flexion-extension and correspondingly a reduction in the cyclic paraspinal muscle activity. The effect of local tissue-electrogoniometer vibration from the surface measurements of the spine in the fore-aft axis is assessed as the electrogoniometer when mounted on the skin can over estimate the true spinal motion of the vertebrae.

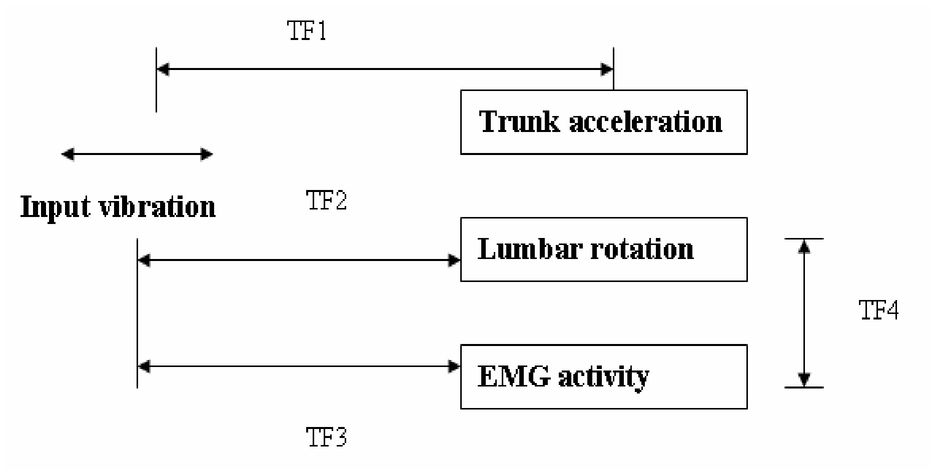


**Figure 1.3: Schematic of transmission functions**

$$TF1_{magnitude} = \frac{acceleration_{spine}}{acceleration_{seat}}$$ Equation 1.5

$$TF2_{magnitude} = \frac{lumbarrotation}{acceleration(input)}$$ Equation 1.6

$$TF3_{magnitude} = \frac{nEMG}{acceleration(input)}$$ Equation 1.7

$$TF4_{magnitude} = \frac{nEMG}{lumbarrotation}$$ Equation 1.8

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# 2 Methods

## 2.0 Subjects

Nineteen healthy subjects (10 male and 9 female, mean age $24 \pm 3$(SD) years, height $1.6 \pm .05$ m (SD), weight $69 \pm 7$ kg (SD)) participated in this study. Subjects were screened with a health history questionnaire to eliminate, those who experienced low back pain and other musculoskeletal disorders in the recent past. The Human Subjects Committee from the University of Kansas approved this study, and all subjects signed an informed consent form prior to participation.

## 2.1 Equipment and signal analysis

Two tri-axial accelerometers, 356 A17 (PCB Piezotronics Inc., Depew, NY), were used to measure acceleration of the seat pan and torso. One accelerometer was mounted on the seat pan to measure the input seat motion. A second accelerometer, oriented along the axis of motion, was mounted on the skin at C-7 of the spinous process with double-sided tape. All data were collected using the Motion Monitor Software interface (Innsport, IL) at a frequency of 1500 Hz. Using the factory reported calibration specifications (Table 1), the output voltage readings of the accelerometer are converted to units of g ($9.8\,ms^{-2}$). Raw accelerometer readings are filtered to remove electrical noise, using notch filters at 60Hz, and multiples of 60Hz. A low pass filter was also applied at 240 Hz.

An electrogoniometer (Biometrics Ltd, Gwent, UK) was used to monitor the flexion and extension of the lumbar spine. The electrogoniometer ends were attached to the skin over the T-12 and S-1 spinous processes respectively using double-sided tape. These locations were chosen to be consistent with previous work examining the neuromotor transmission of vertical seat vibration [84]. The electrogoniometer was used to provide biofeedback of the lumbar posture to the subject via the ADU301 angle display unit interface. Flexion-extension readings were recorded in the voltage format and converted to degrees using the formula:

$$\text{Angle}=90*(\text{voltage}-2.5) \qquad \text{Equation 2.1}$$

Goniometer data was filtered with a 60Hz notch filter and a 240Hz low pass filter.

**Table 1: Accelerometer Calibration Specifications**

| | | |
|---|---|---|
| | Accelerometer 1 Sensitivity (mV/g) | Accelerometer 2 Sensitivity (mV/g) |
| X-Axis | 496 | 517 |
| Y-Axis | 491 | 524 |
| Z-Axis | 508 | 505 |

Eight bipolar surface electromyographic electrodes (Delsys, Boston, MA) were attached to the skin bilaterally over the trunk muscle groups of interest, namely erector spinae (ES), rectus abdominus (RA), internal obliques (IO), external obliques (EO). Two EMG electrodes were placed bilaterally over the ES muscle group at L2/L3 level of the spine with an inter-electrode spacing of 3-4cm. Electrodes were placed over the RA muscle groups, 1-2cm superior to the umbilicus with an inter-electrode spacing of 3-4cm.

Another two electrodes were placed 10 cm lateral to the umbilicus with an orientation of 45° to vertical over the EO muscle group. For IO, electrodes were placed 8-10 cm lateral to the midline with in the lumbar triangle at a 45° orientation to the vertical. The measurements from the surface EMG electrodes were recorded at a sampling frequency of 1500Hz on a 16 channel A/D board. Signals from the surface electrodes were amplified with a gain of 1000. The frequency of an EMG signal has been shown to be within 0 to 500Hz with the majority of the usable energy between 50-150Hz [85]. Forward and reverse butterworth filters were used to band-pass filter the EMG between 20-250Hz. To eliminate the contamination of signals from electrical noise, raw EMG data were filtered with several notch filters setup at 60Hz and multiples of 60Hz. The EMG data were demeaned, rectified, and integrated with a 100 point Hanning window.

## 2.2 EMG normalization

EMG signals were normalized with the maximum voluntary muscle contraction to reduce inter-subject variability. Prior to initiation of the vibration protocol, subjects were instructed to lie down on a bench, and their lower extremities and hip were strapped against the bench. The subjects were instructed to do a series of maximal flexion, extension, clockwise and counterclockwise exertions while their shoulders were held stationary by an investigator. For the maximal extension exertions, the subjects lay prone and were instructed to raise their chest off from the bench to complete a back extension while the investigator held the shoulders in place. These exertions were used to determine the maximum EMG activation for the ES group muscle. The subjects then lay supine on the bench; with their shoulders held in place, they were instructed to attempt to lift their torso against resistance by the investigator in order to assess maximum EMG activation for the RA muscle group. Finally with an investigator holding one shoulder at a time, the subjects were instructed to attempt to twist both clockwise and counter clockwise. This motion was used to assess IO and EO maximum muscle activity.

## 2.3 Vibration exposure seating and the shaker table

A rigid seat (500mm **x** 400mm) made of wood was installed on a Ling 1512 electro-dynamic horizontal vibration shaker. The seat had a backrest, which was 555mm **x** 630 mm wide, and provides support for the occupants upper back while leaning against it. The unpadded seat was installed on the vibration platform, which consisted of a slip table on an oil film over a granite table. A schematic of the shaker setup is shown in Figure 1. The shaker was powered by a DMA 2/X solid state power amplifier (Anaheim, CA). Control for the shaker was provided by a DAKTRON shaker control system (Fremont, CA). This controller allows the instructor to deliver sinusoidal vibration with frequencies ranging from 3 to 14 Hz at magnitudes of 1 RMS and 2RMS. In this study, the shaker controller was set to create a constant frequency and magnitude vibration at intensities of 1RMS and 2RMS.

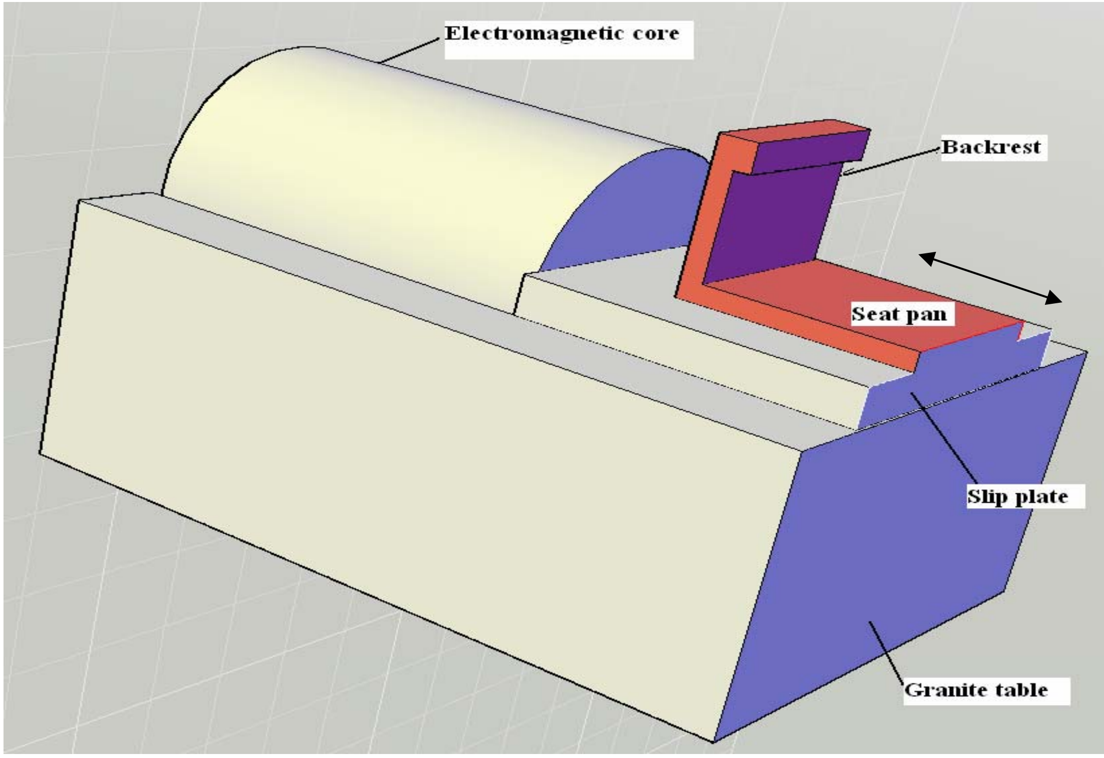


**Figure 2.1: Schematic of shaker setup**

## 2.4 Vibration exposure protocol

Once preliminary EMG maxes were collected, the subjects were instructed to sit carefully in the unpadded seat on the shaker table. The subjects were instructed to adopt a comfortable posture; the angle display unit of the electrogoniometer was zeroed after the posture was adopted. For the remainder of the study the subjects were asked to maintain this zeroed posture in all test conditions.

During the dynamic vibration test; the data (EMG, accelerometer, and electrogoniometer data) were recorded on the seated subjects for each trial. Trials included two different back support conditions: with and without a backrest (i.e BACK ON and BACK OFF). With the backrest (BACK ON) condition, subjects relaxed their thoracic back against the backrest (Figure 2). Without the backrest (BACK OFF) condition, subjects sat without leaning on the backrest (Figure 3). The subjects were instructed to maintain the same consistent lumbar posture during with and without the backrest by using the electrogoniometer biofeedback to assess this posture. During the dynamic vibration test, the measurements were performed for each subject assuming two different seating conditions i.e., with and without a backrest.

Seating conditions (BACK ON, BACK OFF), vibration frequency (3, 4, 5, 6, 8, 10, 11, 12,14Hz) and vibration intensity (1 and 2 RMS $ms^{-2}$) were the independent variables in this study. A total of 36 (9 frequencies, 2 vibration intensities, and 2 back rest conditions) trials were conducted, with each trial lasting for a time period of 40 seconds. Rest times of approximately 10seconds were allowed between trails and approximately 2 minutes rest time is given between different sitting postures. Rest times were given to prevent fatigue and subjects were instructed to resume the initial posture before each successive trial.

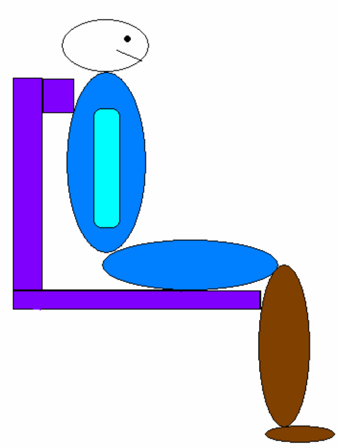

**Figure 2.2:Schematic of BACK ON condition**

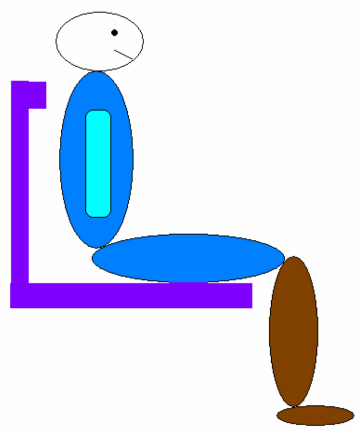

**Figure 2.3:Schematic of BACK OFF condition**

The order of presentation of vibration frequency within each magnitude condition and vibration magnitude was block randomized. The order of sitting postures was also block randomized. The whole body vibration exposure duration was 24 minutes, keeping the total setup and testing duration in a controllable time frame of 2 hrs.

## 2.5 Examination of skin motion artifacts and its estimation

A sub study was done to assess the effect of skin motion artifact from surface measurement of vibration over the spine. Two healthy subjects with a mean age group of $25 \pm 2$(SD) participated in the Free Oscillation test. An electrogoniometer was attached to the skin, such that the two goniometer ends coincided with the T-12 and S-1 spinous processes. To obtain a damped free oscillation, the skin was gently pulled outwards in the fore-aft (normal) direction of the tissue. Oscillations were obtained in the fore-aft (normal) direction of the tissue, which were simultaneously recorded on a NI 6020E 16-bit A/D board at a sampling rate of 1500Hz for a duration of 2 seconds, leading to a data array consisting of 3000 data points. The raw data was filtered using a 100-point Hanning window. The filtered raw data of the free vibration (oscillation) test was further processed to assess the damping ratio ($\xi$) and the angular natural frequency ($\omega_n$) of the local system.

All data processing was performed in MATLAB (Math works, Natick, MA). The filtered data was demeaned by subtracting the mean from the filtered signal. Peak values $x_i$ , $x_{i+1}$.. were determined. The start point was set from the first minimum of the first cycle. The magnitudes of maximum peak amplitudes and the minimum peak amplitudes along with their corresponding time index were assessed (Fig 4). The absolute values of this peak were fit to the equation 2.2 using a linear regression of log of amplitude with respect to time.

$$\text{mag} = Ae^{-\sigma t} \qquad \text{Equation2.2}$$

The logarithmic decrement $(\xi * \omega_n)$ was obtained from the slope of the linear regression. The correction frequency function [64, 65] was calculated by substituting the natural angular frequency and the damping ratio in the correction frequency function equation $\boldsymbol{T(\xi, \omega_n)}$.

$$T(\omega_n,\xi)=\sqrt{\frac{1+(2\xi\omega/\omega_n)^2}{(1-(\omega/\omega_n)^2)^2+(2\xi\omega/\omega_n)^2}}$$ Equation 2.3

Where $\omega_n$ is the natural angular frequency, $\omega$ is the excitation angular frequency, and $\xi$ is the damping ratio. The correction frequency function was used with rotations measured on skin ($R_s$) to assess the rotations measured on bone ($R_b$). $R_s$ was the rotations measured on the skin when the subjects were exposed to dynamic vibrations.

$$R_b = T(\omega_n,\xi)^{-1} * R_s$$ Equation 2.4

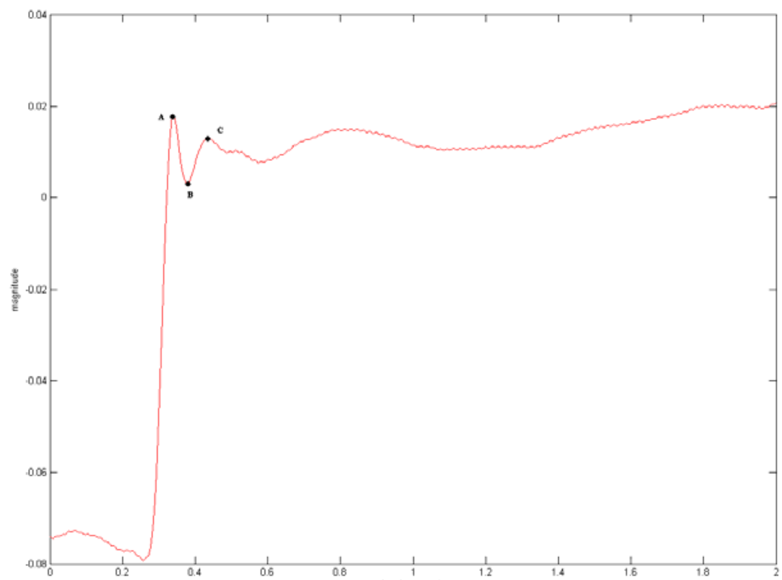


**Figure 2.4:Free oscillation test conducted on subject 18, magnitudes of A, B, and C along with their respective time indices were picked to assess damping factor.**

## 2.6 Running average method for dynamic vibration test

A running average method was used to analyze the cyclic sinusoidal signals. Forty cycles were averaged to obtain a single, ensemble average of a vibration cycle. To avoid any phase information loss, the input (acceleration of seat pan) and the output EMG, electrogoniometer, and acceleration signals were averaged at the same time instant .The start point was set from the maximum of the first cycle, then the entire signal is split in to several cycles. Length of cycle was determined by data sampling frequency divided by the vibration test frequency. Average magnitude of each signal is obtained by taking the difference of the magnitude of crest and trough of the ensemble averaged signal. Magnitudes of the TF were obtained by the ratio of the average magnitudes of the output and input signals. Delay time is a measure of the offset in time between the maximum peak of the input and the maximum peak of the output.

## 2.7 Transmissibility functions

Acceleration of seat pan, acceleration of spine, EMG, and lumbar rotations data were assessed using the four transmission functions (TF's). All data processing is performed on MATLAB software.

Mechano-NeuromotorTransmission ($\mathbf{TF4_{magnitude}}$) of horizontal seat pan vibration is defined as the ratio in magnitude between neuromuscular activation measured as the normalized EMG magnitude and lumbar flexion-extension rotations measured by the electrogoniometer. $\mathbf{TF3_{magnitude}}$ represented the ratio of vibration induced EMG muscle activity to the seat pan acceleration. $\mathbf{TF2_{magnitude}}$ and $\mathbf{TF1_{magnitude}}$ represented the ratio in magnitude of lumbar rotation and the spine acceleration to the seat pan acceleration.

$$TF1_{magnitude} = \frac{acceleration_{spine}}{acceleration_{seat}}$$ Equation 2.5

$$TF2_{magnitude} = \frac{lumbarrotation}{acceleration(input)}$$ Equation 2.6

$$TF3_{magnitude} = \frac{nEMG}{acceleration(input)}$$ Equation 2.7

$$TF4_{magnitude} = \frac{nEMG}{lumbarrotation}$$ Equation 2.8

Delay times were calculated from the ensemble averaged signal. Delay time was a measure of difference in time between the peak occurrence of output and input variables and was calculated for **TF3** and **TF4**.

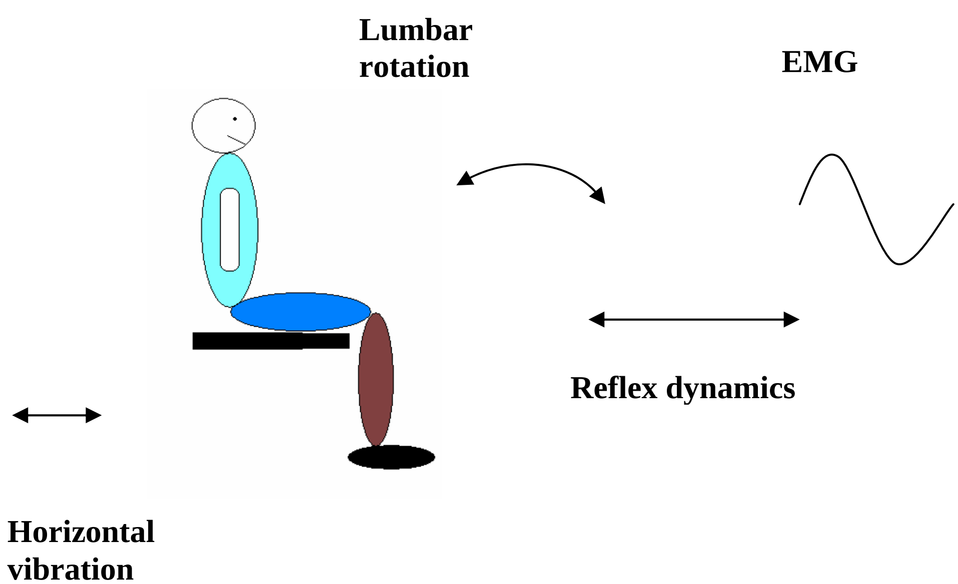


**Figure 2.5: Schematic of Mechano-neuromotor transmission**

## 2.8 References

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3. Kitazaki, S. and Griffin, M. J. A data correction method for surface measurement of vibration on the human body. J Biomech **28**, 885-890, 1995.
4. Hinz, B., Seidel, H., Brauer, D., Menzel, G., Bluthner, R. and Erdmann, U. Examination of spinal column vibrations: a non-invasive approach. Eur J Appl Physiol Occup Physiol **57**, 707-713, 1988.

# 3 Results

Transmissibility functions (TF1-TF4) were calculated for both with and without the backrest conditions (BACK OFF & BACK ON), using the running average method. Delay times were calculated between vibrations-induced EMG and lumbar-rotations induced EMG. Phase responses of vibrations-induced EMG (TF3) and lumbar-rotations induced EMG (TF4) were represented in this section.

## 3.0 Transmission functions without a backrest

Trunk acceleration transmissibility (TF1) exhibited a gradual decline with increasing frequency with a small bump at 5Hz (Figure 3.1). Average transmission for the entire frequency range differed by 8.33% between 1 RMS ($ms^{-2}$) and 2 RMS ($ms^{-2}$) input magnitudes.

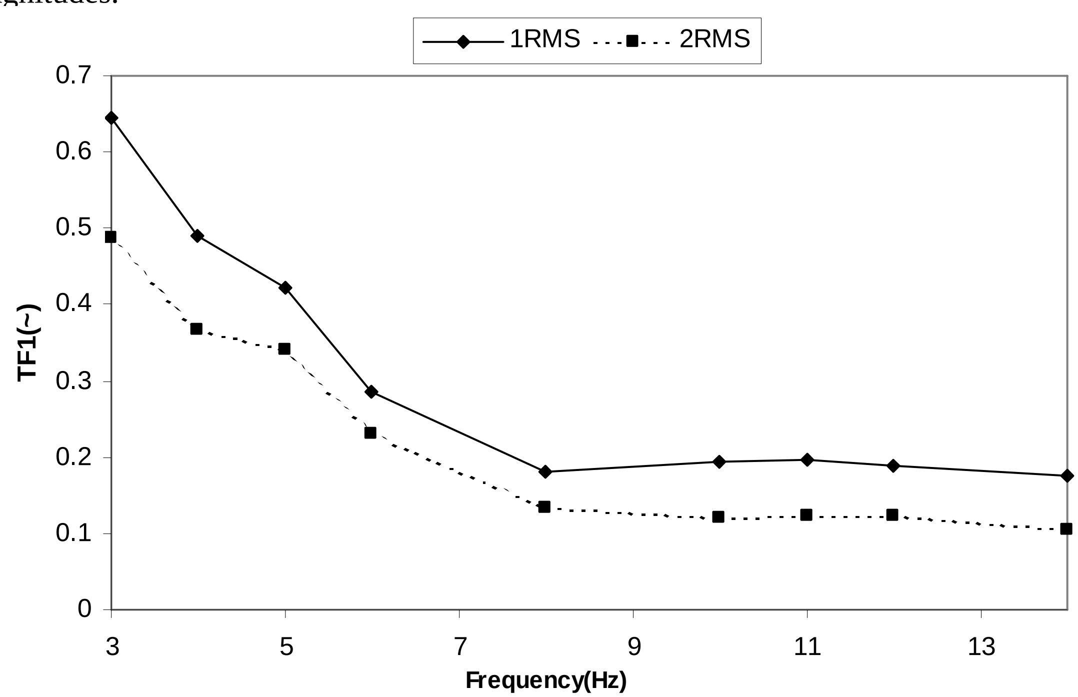


**Figure 3.1: TF1 transmission of acceleration to the spine**

The ratio of the vibration induced lumbar rotations to that of the input vibration intensity (TF2), exhibited a gradual decline with increasing frequency (Figure 3.2). Average transmission for the frequency range differed by 7.42% between 1 RMS ($ms^{-2}$) and 2 RMS ($ms^{-2}$) magnitudes.

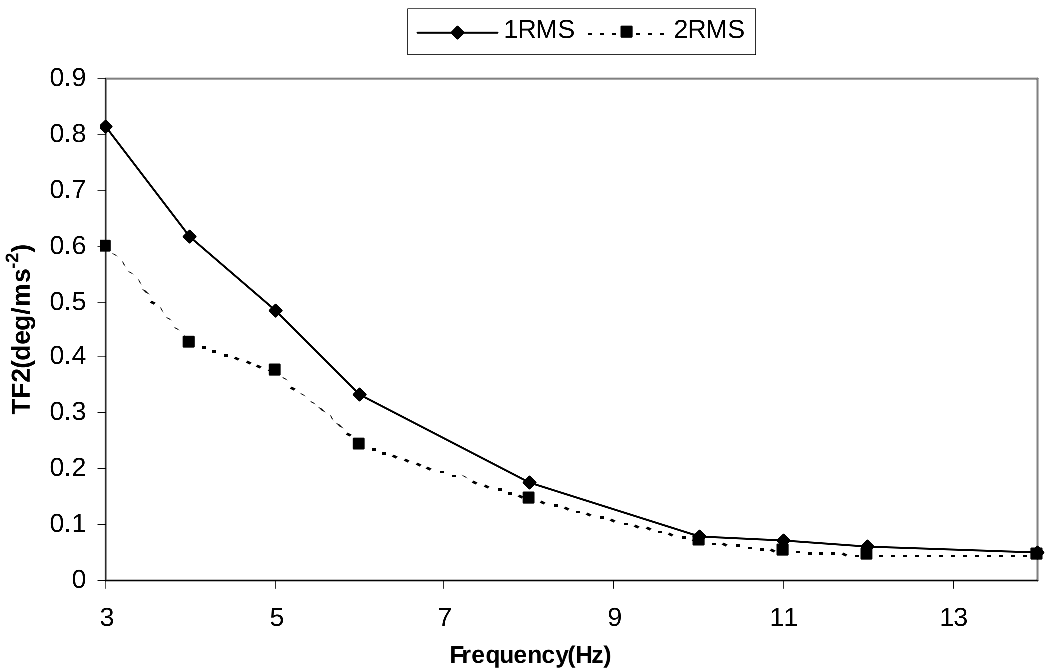


**Figure 3.2: TF2 magnitude exhibiting a gradual decline with increasing frequency**

Vibration induced EMG as a function of input acceleration (TF3), exhibited a peak at 6 Hz for 2 RMS ($ms^{-2}$) magnitude, and at 5 Hz for the 1RMS ($ms^{-2}$) magnitude (Figure

3.3). Average difference for the entire frequency range was .016% different between the lower (1 RMS) and higher (2 RMS) magnitudes.

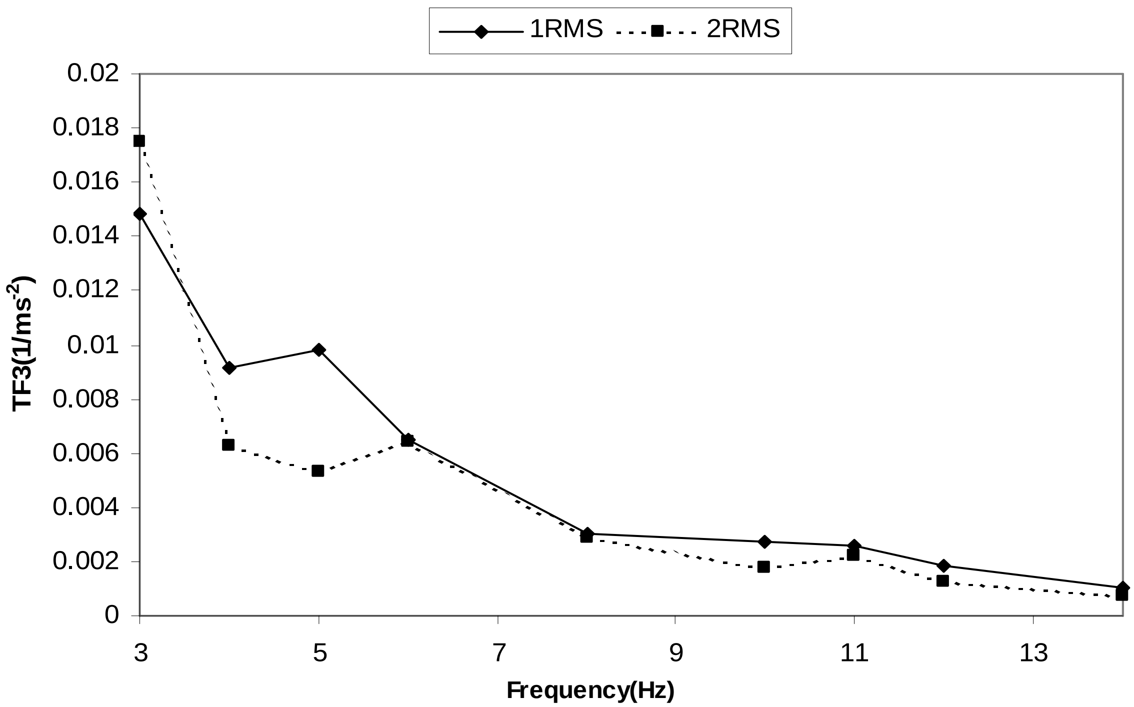


**Figure 3.3: TF3 exhibiting a gradual decline with increasing frequency with a small peak at 6 Hz for 2 RMS($ms^{-2}$) and at 5 Hz for 1 RMS($ms^{-2}$) with BACK-OFF condition**

The Mechano-neuromotor Transmission (MNT) of input sinusoidal vibration (TF4) describes the response of erector spinae muscle group to vibration induced lumbar rotations. It was found to have relatively constant transmission with a small peak at 6 Hz and a large peak at 11 Hz for 2 RMS ($ms^{-2}$) magnitude. For the lower vibration (1RMS $ms^{-2}$) magnitude, the MNT exhibited a small peak at 5 Hz and a localized peak at 11 Hz (Figure 3.4).At frequencies higher than 10 Hz, magnitudes of lumbar rotations and nEMG were small, making the data at these frequencies susceptible to noise. As the peak exhibited at 11 Hz is more prone to noise rather than muscle activation, it may be a noise artifact.

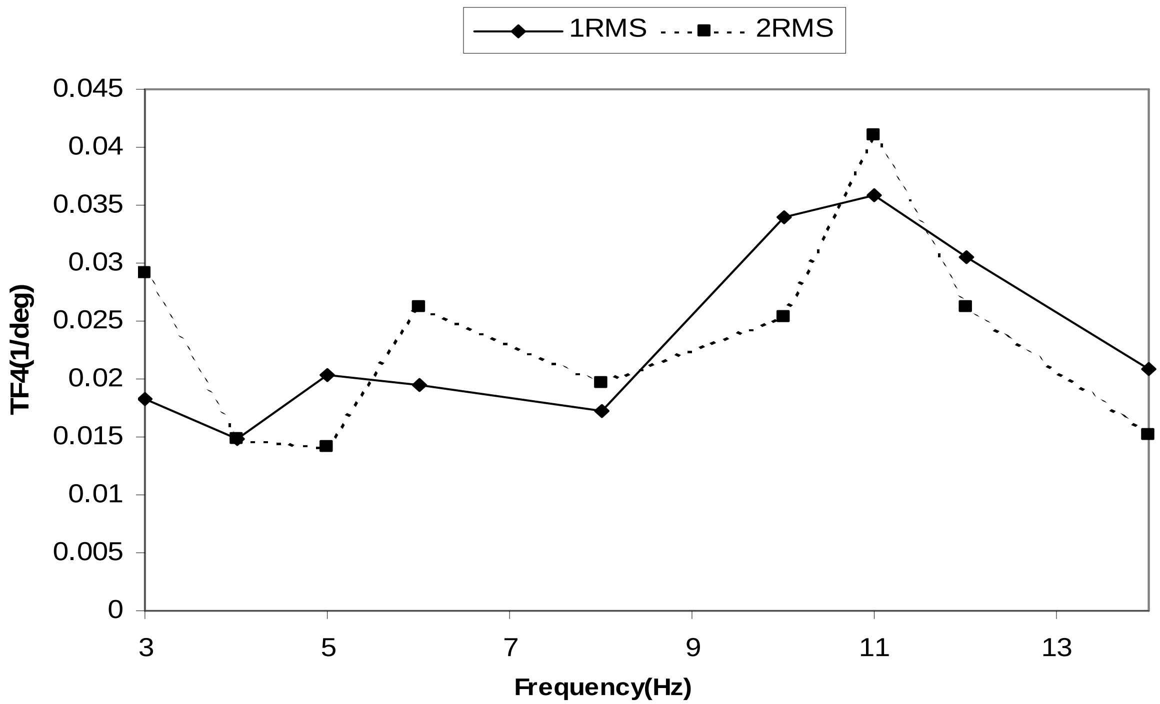


**Figure 3.4: TF4(MNT) exhibited a peak at 11 Hz for both intensities and a peaks similar to that of TF3 at 5 Hz for 1 RMS($ms^{-2}$) and at 6 Hz for 2 RMS ($ms^{-2}$) respectively with BACK-OFF condition**

## 3.1 Delay time

Delay time is a measure of the offset in time between the maximum peak of input and maximum peak of the output. Averaged time delay for all subjects between input acceleration and vibration induced muscle activity (*delay1*) decreased with increasing frequency when vibration was applied with out the backrest (Figure 3.5). nEMG lagged behind input acceleration by ~390-384 ms at 3 Hz to 41-37 ms at 14 Hz. Average time delay for all subjects between vibrations induced back rotations and nEMG (*delay2*) showed a similar trend and decreased gradually with increasing frequency(Figure 3.6) in without backrest condition. nEMG lagged behind vibrations induced back rotations by 184-180 ms at 3 Hz to 29-28 ms at 14 Hz. Delay 1 averaged over the frequency range dropped from ~156 ms at 2 RMS($ms^{-2}$) vibration magnitude to ~143 ms at 1 RMS($ms^{-2}$). Delay2 averaged over the frequency range dropped from ~92ms at 2 RMS($ms^{-2}$) vibration magnitude to ~84 ms at 1 RMS($ms^{-2}$).

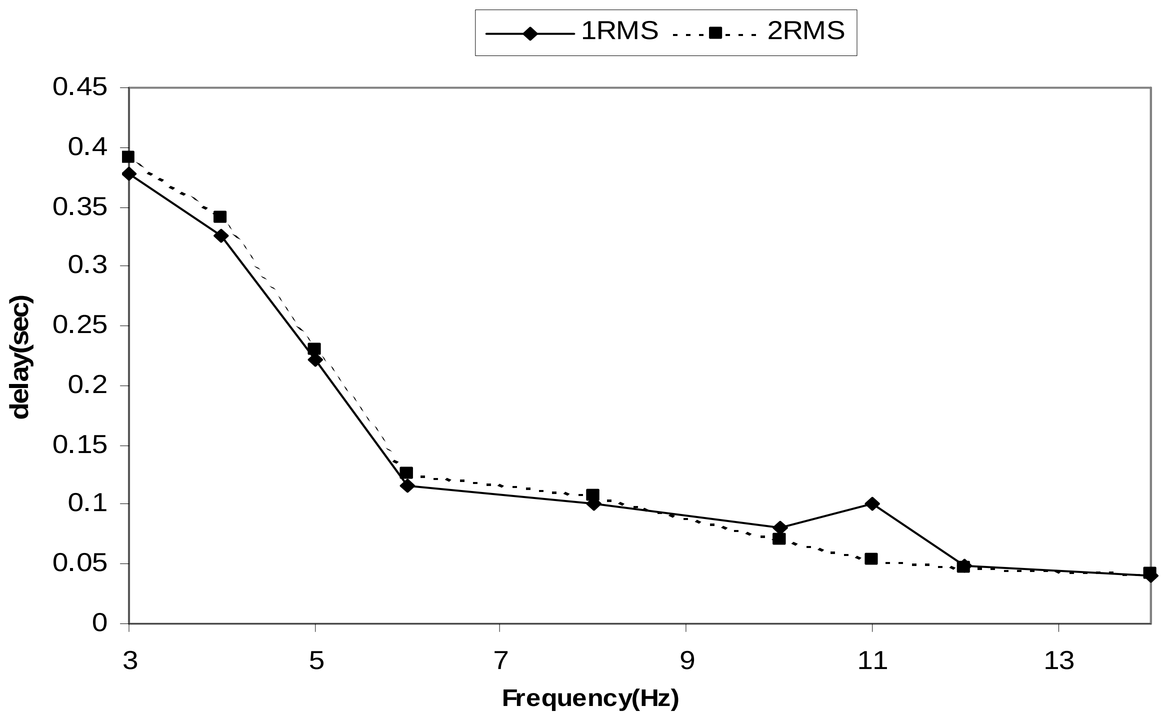


**Figure 3.5: delay time measured between maximum peak input acceleration and peak nEMG activation exhibited a decline with increasing frequency from 390 ms at 3 Hz to 41 ms at 14 Hz**

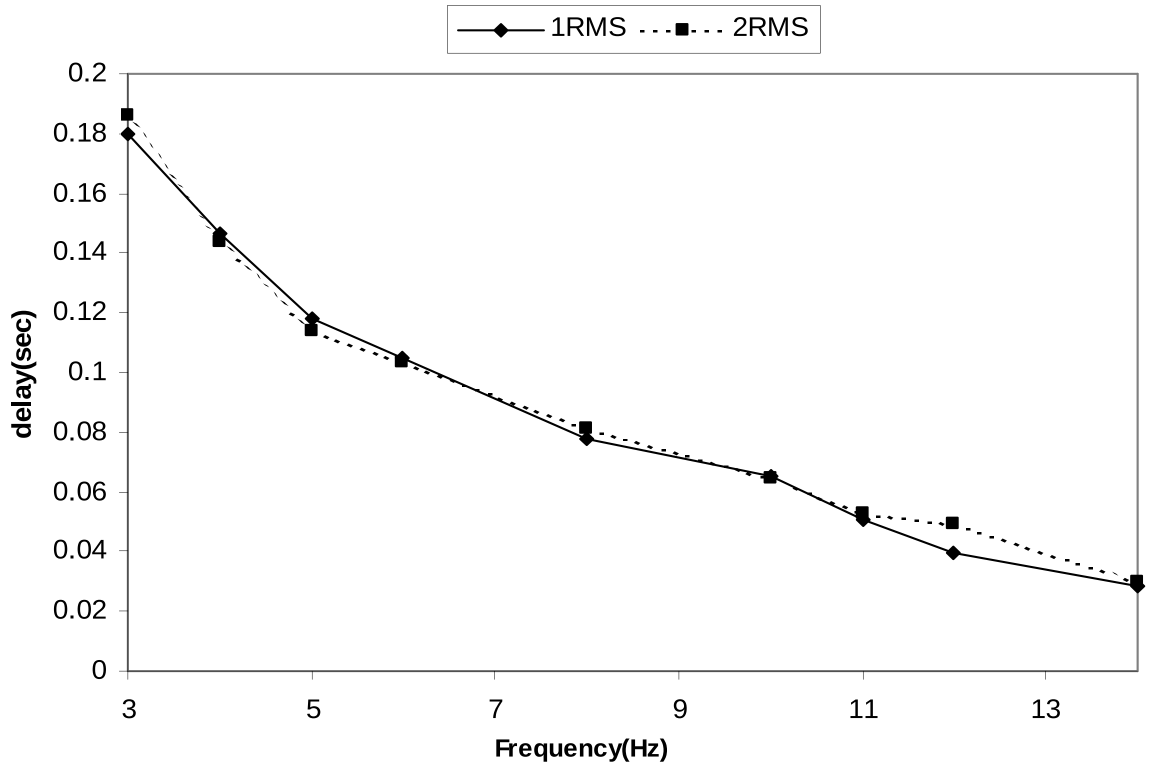


**Figure 3.6: delay time measured between peak vibrations induced lumbar rotations and peak nEMG activation exhibited a gradual decline with increasing frequency from 184 ms at 3 Hz to 28 ms at 14 Hz**

The ratio of delay time ( $\Delta T$ ) to that of the cycle period is used to assess the phase response .The phase response is normalized to $360^0$. Based on the hypothesis that EMG follows lumbar rotations which is further followed by induced vibration, the phase responses between vibration-induced EMG as a function of input acceleration (TF3) & response of erector spinae muscle group to vibration induced lumbar rotations (TF4) were represented in figures 3.7 & 3.8.

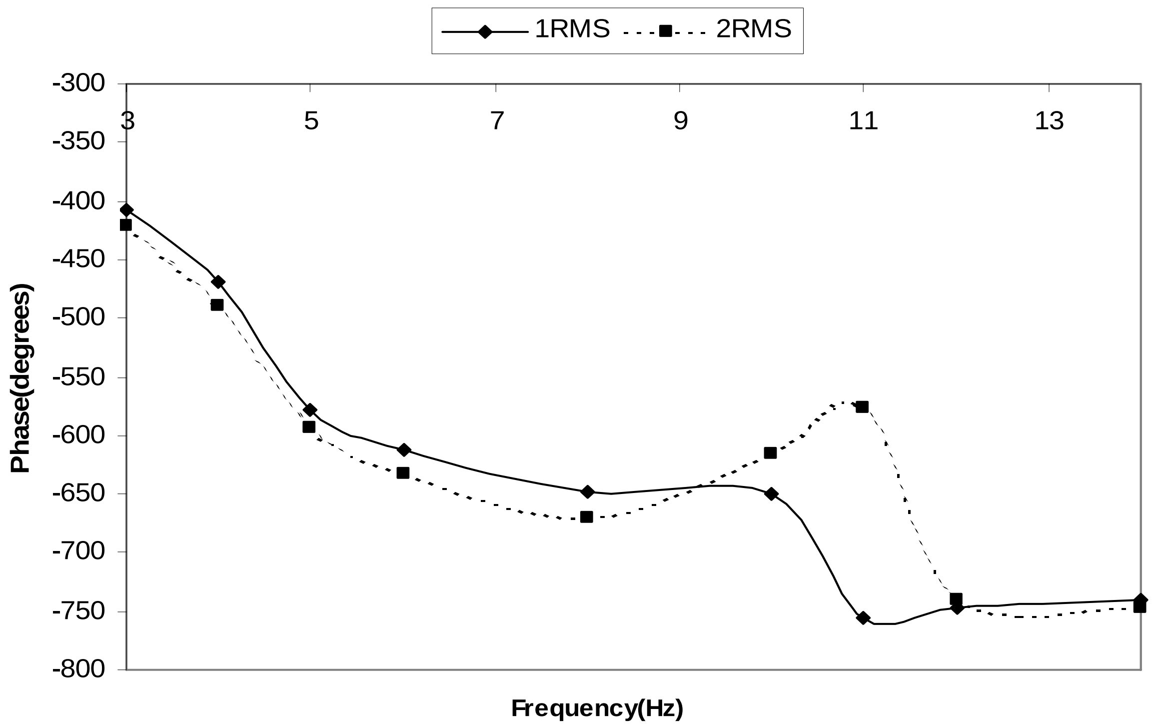


**Figure 3.7: Phase response of TF3**

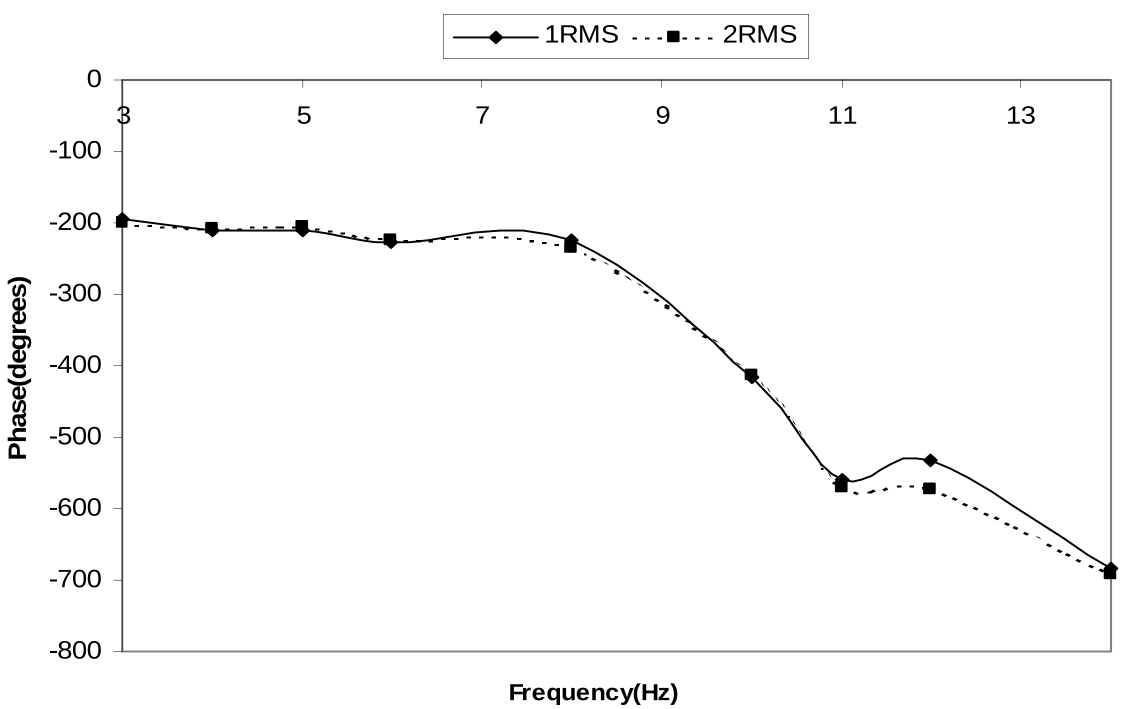


**Figure 3.8: TF4 phase response**

## 3.2 Transmission functions with a backrest

Trunk acceleration exhibited a decline with increasing frequency. The transmissibility of the induced vibrations exhibited resonance characteristics in the frequency range 3-6 Hz for both intensities. The TF1 with the backrest exhibited a gradual decline between 3-8 Hz and leveled off from 8 Hz –14 Hz (Figure 3.9). Average transmission for the frequency range differed by 7.89% between the lower and higher vibration magnitudes.

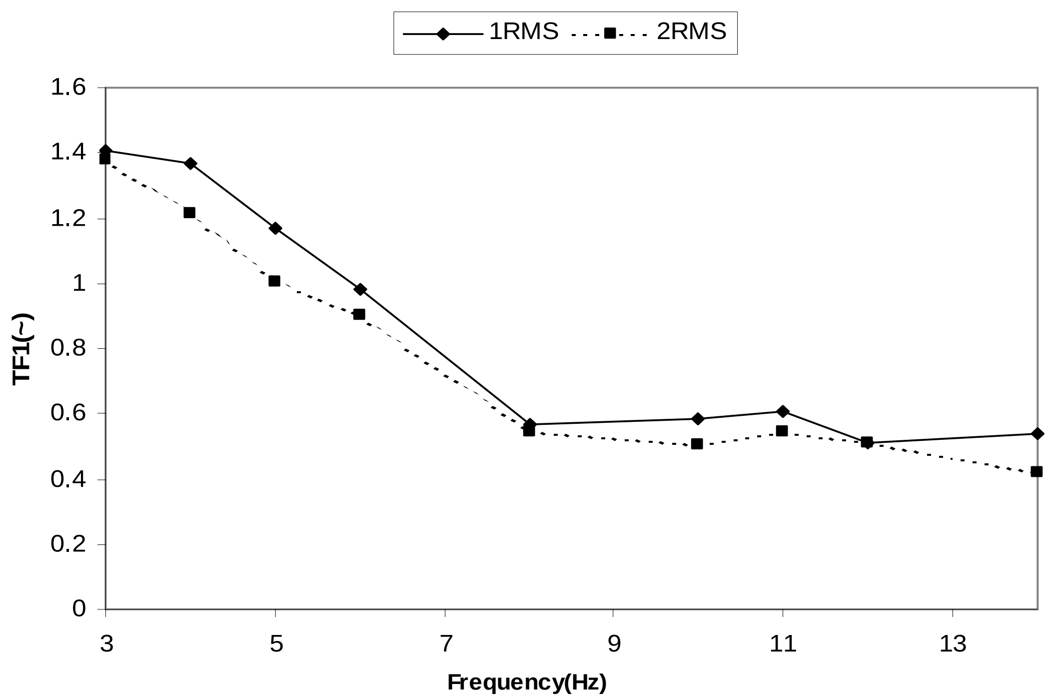


**Figure 3.9: TF1 transmission of acceleration to the spine (C-7 of spinous process) with BACK-ON condition exhibited a gradual decline with increasing frequency and with exhibiting transmissibility greater than 1 from 3-6 Hz**

TF2 vibration induced lumbar rotations were found to decline with increasing frequency (Figure 3.10) with the backrest. Average transmission for the frequency range differed by 7.3% between the higher and lower vibration magnitudes.

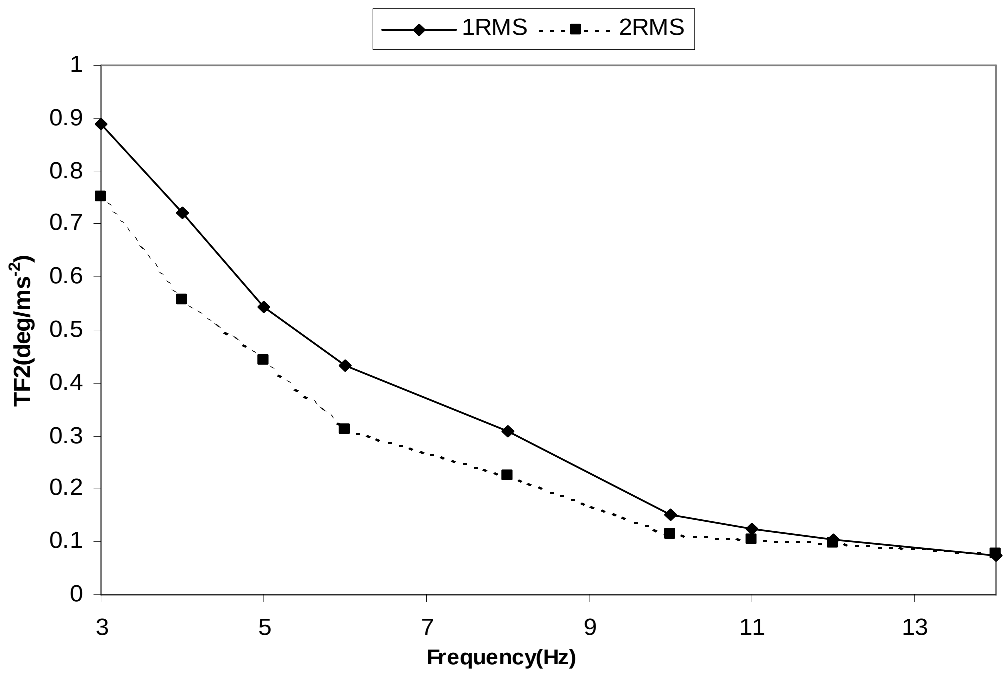


**Figure 3.10: TF2 magnitude exhibiting a gradual decline with increasing frequency with BACK-ON condition**

nEMG as a function of input acceleration (TF3) was found to have a gradual decline with increasing frequency, exhibiting a peak at 8 Hz for 2 RMS ($ms^{-2}$) magnitude and a peak at 6 Hz for 1RMS ($ms^{-2}$) magnitude (Figure 3.11). A smaller peak is exhibited at 11 Hz and 12 Hz for 1 RMS ($ms^{-2}$) and 2 RMS ($ms^{-2}$) intensities respectively. A gradual decline in magnitude of transmissibility function from 3-5 Hz is exhibited (Figure 3.11) with backrest condition.

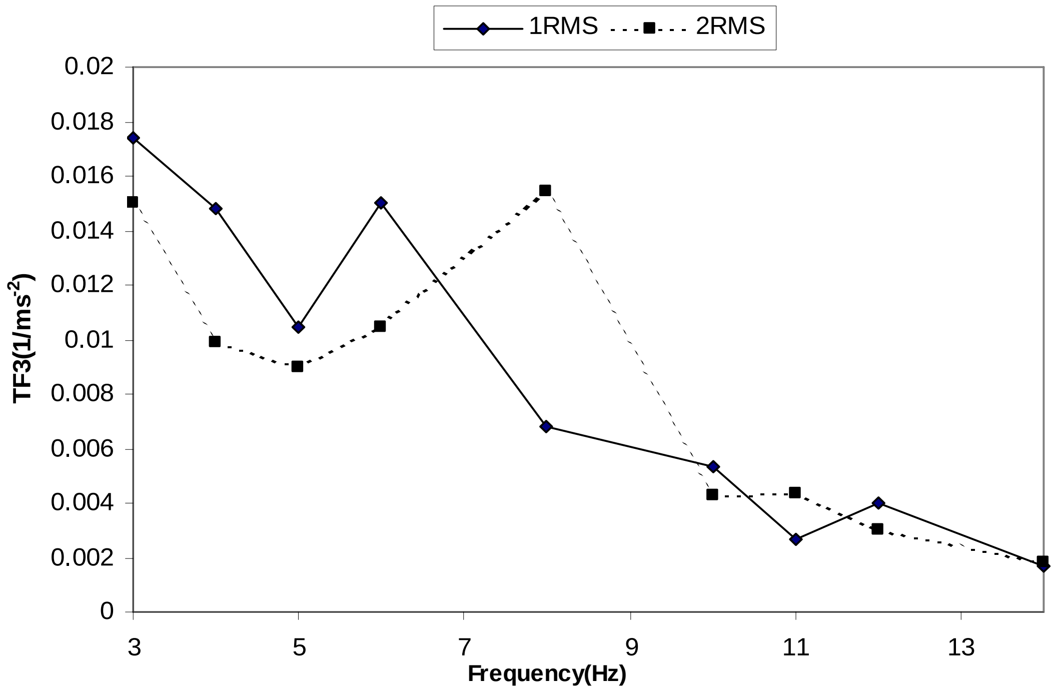


**Figure 3.11: TF3 showed a gradual decline with increasing frequency and peaking at 6 Hz and 8 Hz for 1 RMS ($ms^{-2}$) and 2 RMS ($ms^{-2}$) intensities with BACK-ON condition**

Mechano-neuromotor transmissibility (TF4) was found to have a relatively constant transmission with increasing frequency, exhibiting a huge peak at 8 Hz for 2RMS ($ms^{-2}$) intensity. A small peak is observed at 11 Hz for 2 RMS ($ms^{-2}$) intensity and at 12 Hz for 1 RMS ($ms^{-2}$) intensity. A small peak is observed at 6 Hz and 10 Hz, 1 RMS ($ms^{-2}$) intensity (Figure 3.12). The peaks exhibited at higher frequencies are more prone to noise rather than muscle activity, and can thus be ignored.

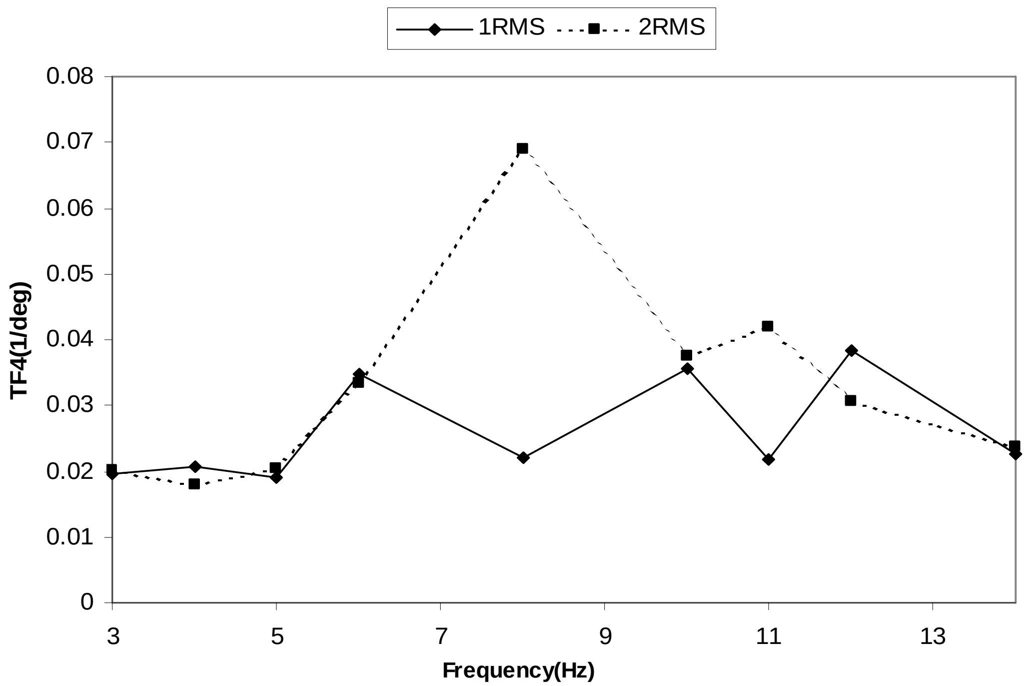


**Figure 3.12: TF4 (MNT) exhibited a peak at 8 Hz for 2 RMS ($ms^{-2}$) intensity and at 6 Hz for 1 RMS ($ms^{-2}$) intensity. A small peak is exhibited at 11 Hz, 2RMS and 10 Hz, 12 Hz 1RMS intensity**

## 3.3 Delay times with a backrest

Averaged time delay for all subjects between input acceleration and vibration induced muscle activity (*delay1*) decreased with increasing frequency (Figure 3.13) with a backrest. nEMG lagged behind input acceleration by ~363 ms at 3 Hz to 43 ms at 14 Hz. Average time delay for all subjects between vibrations induced back rotations and nEMG (*delay2*) showed a similar trend and decreased gradually with increasing frequency (Figure 3.14) with BACK ON condition. nEMG lagged behind vibrations induced back rotations by 180 ms at 3 Hz to 29 ms at 14 Hz. Phase response of TF3 is represented in figure 3.15. The muscle activity is observed to lag behind the input acceleration by one cycle (Figure 3.15). With increasing frequency the muscle activity is observed to lag behind the input acceleration. (Figure 3.16). Delay1 averaged over the frequency dropped from ~144 ms at 1RMS ( $ms^{-2}$ ) vibration magnitude to ~138 ms at 2RMS ($ms^{-2}$). Delay2 averaged over the frequency range dropped from ~89 ms at 1 RMS ($ms^{-2}$) vibration magnitude to ~84 ms at 2 RMS ($ms^{-2}$).

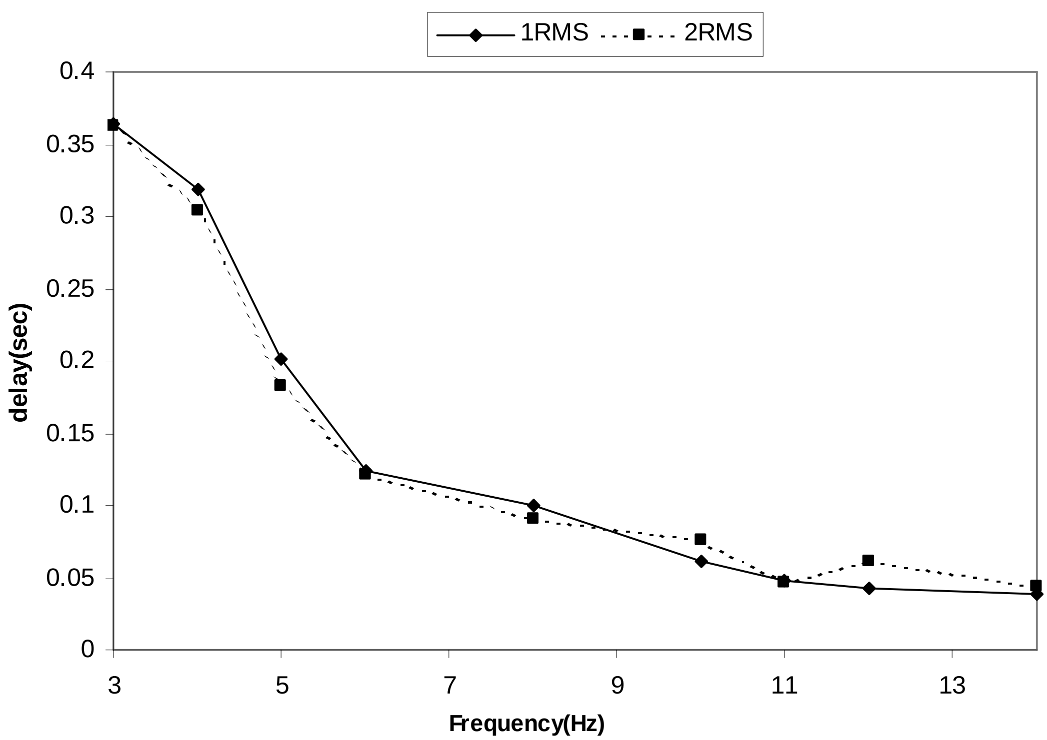


**Figure 3.13: delay time measured between peak input acceleration and peak nEMG activation showed a gradual decrease with increasing frequency from 363 ms at 3 Hz to 43 ms at 14 Hz with BACK-ON condition**

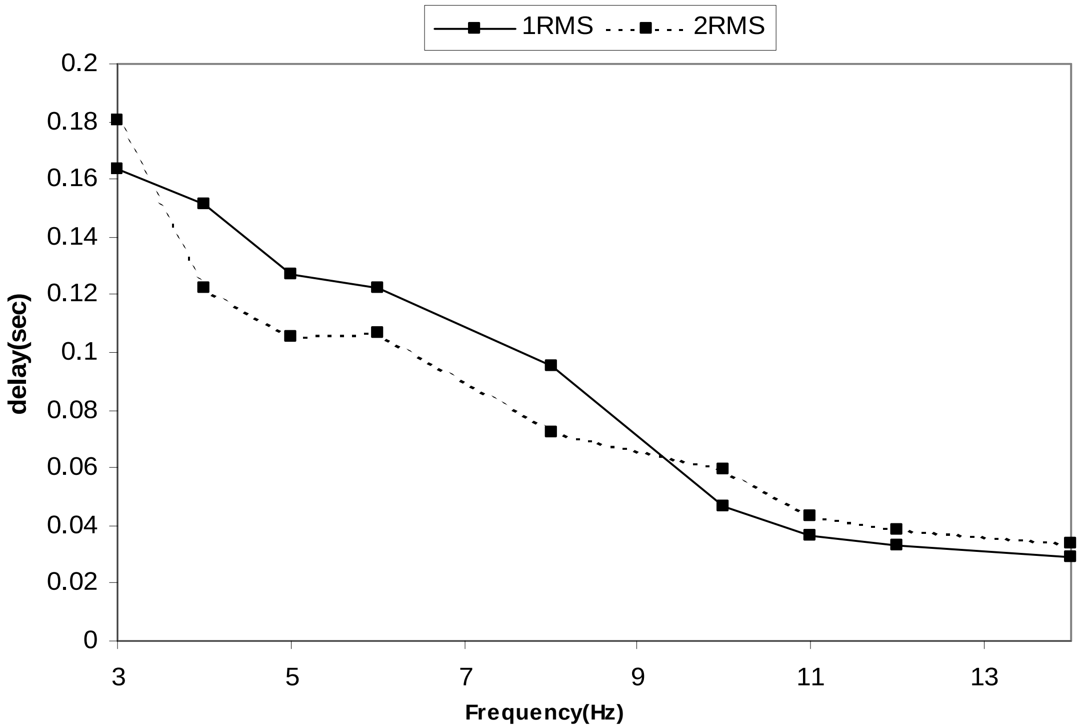


**Figure 3.14: delay time measured between vibrations induced lumbar rotations and peak nEMG activation showed a gradual decrease with increasing frequency from 180 ms at 3 Hz to 29 ms at 14 Hz with BACK-ON**

Phase response between the trunk rotations induced nEMG exhibited a lag by half a cycle. With increasing frequency the lag in phase is exhibited. Calculated phase responses of TF3 and TF4 with a backrest were represented in figure 3.15 and 3.16. At low frequencies the phase response of TF4 exhibited a constant lag between the vibration induced lumbar rotations and myo-electric activity.

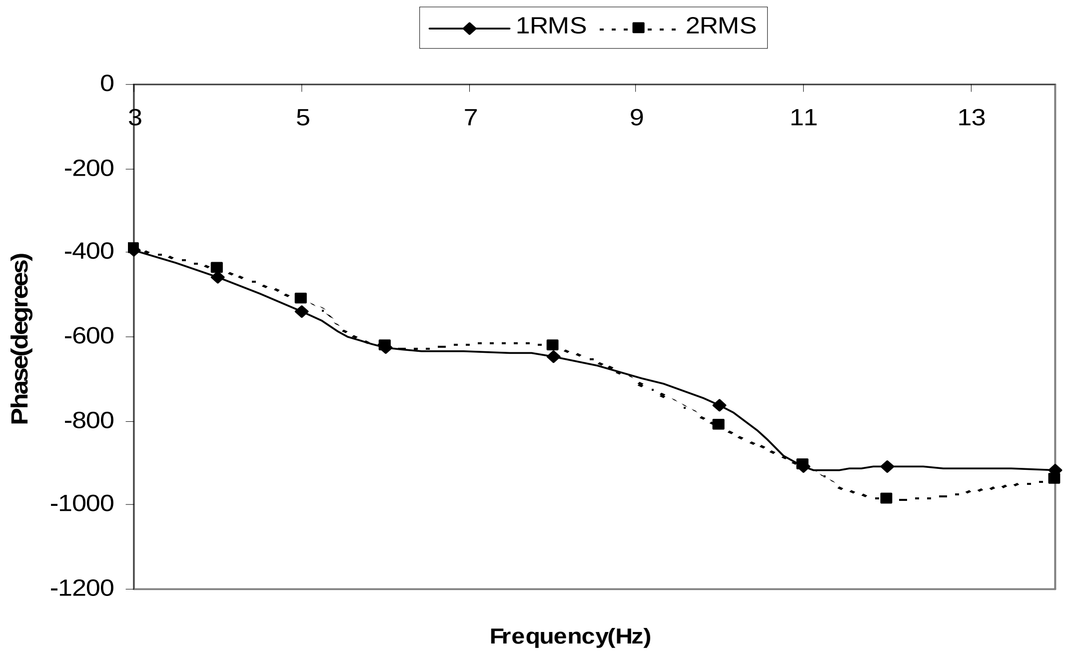


**Figure 3.15: Phase response of TF3 with BACK-ON condition**

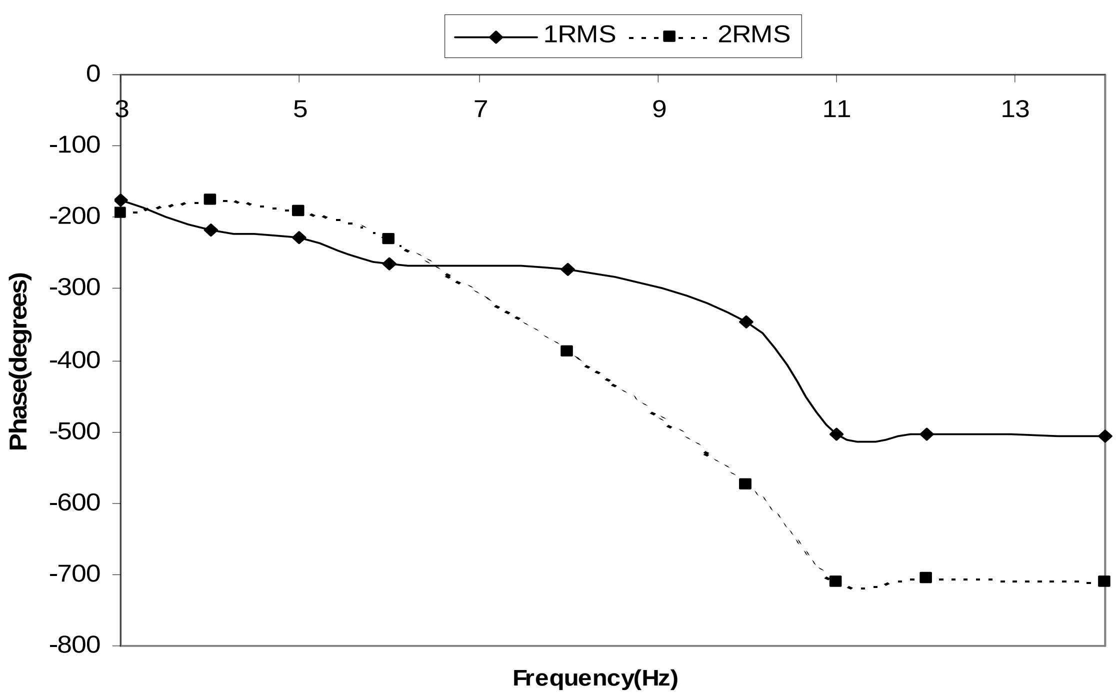


**Figure 3.16: Phase respone of TF4 with BACK-ON condition**

## 3.4 Estimation of lumbar rotations on bone using correction factor and rotations measured on skin

Using the electrogoniometer stuck on the spinous process the lumbar rotations of the spine were measured. The instrument when mounted on the skin can over estimate the true spinal motion since direct contact with the vertebrae is not made. The correction frequency function was used with rotations measured on the skin ($R_s$) to assess the rotations measured on the bone ($R_b$). The correction frequency factor (C.F) was estimated from the correction frequency function equation for the investigated frequency range of 3-14 Hz. To assess the rotations measured on the bone the rotations measured on the skin were corrected by multiplication with the estimated correction frequency factor (C.F) in the frequency range 3-14 Hz. The assessed rotations on the bone for both 1RMS and 2RMS magnitudes were less than 6.8% different (Table 3.1) in the fore-and-aft direction (Figure 3.17).

| Freqeuncy(Hz) | CF | 1RMS | 2RMS | CF*1RMS | CF*2RMS |
|---|---|---|---|---|---|
| 3 | 0.99185 | 3.92705 | 7.26455 | 3.89726734 | 7.206123385 |
| 4 | 0.9855 | 2.7621 | 5.1284 | 2.72168646 | 5.05127655 |
| 5 | 0.97725 | 2.4188 | 3.4967 | 2.36176501 | 3.419439725 |
| 6 | 0.9721 | 2.30855 | 2.9944 | 2.240187005 | 2.90661192 |
| 8 | 0.9675 | 1.42035 | 1.89615 | 1.375860225 | 1.835166325 |
| 10 | 0.95875 | 0.5827 | 0.5023 | 0.561469085 | 0.48200947 |
| 11 | 0.9498 | 0.416 | 0.417 | 0.3966579 | 0.39586992 |
| 12 | 0.94185 | 0.28715 | 0.39105 | 0.27064359 | 0.36810207 |
| 14 | 0.9318 | 0.26205 | 0.43595 | 0.24422304 | 0.40631076 |

**Table 3.1: Rotations measured on the skin (1 RMS & 2RMS) along with CF (Correction factor) were used in estimating the rotations measured on the bone (CF * 1RMS & CF * 2 RMS)**

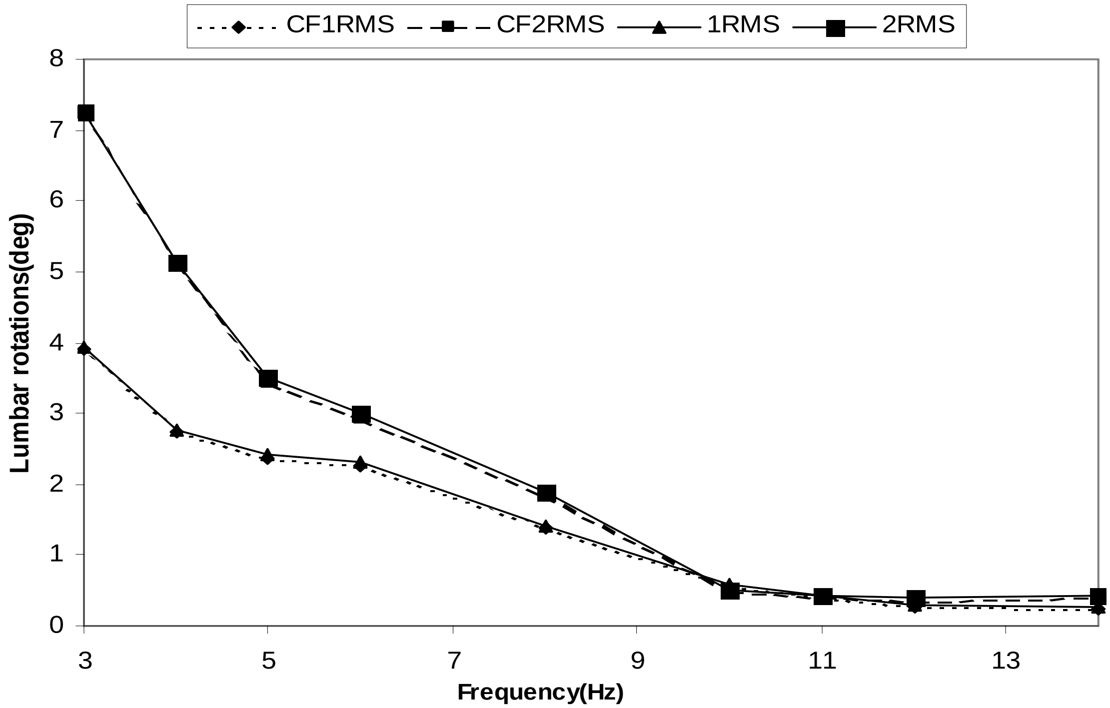


**Figure 3.17: Comparision of mean lumbar rotations of two subjects with before and after correction from horizontal seat to fore-and-aft T-12 rotations**

## 3.5 Comparison of Transmission Functions with and without the backrest

The calculated transmission function magnitudes with and without a backrest conditions were compared in figures (3.18-3.21).

The measured trunk acceleration transmission function magnitudes with the backrest condition exhibited resonance characteristics at low frequencies (3-6 Hz). The resonance behavior at low frequencies is a cause of the larger motion of the thoracic region, which is induced during interaction with the vertical backrest. The transmissibility at low frequencies (3-6 Hz) is greater than one with a backrest condition (Figure 3.18).

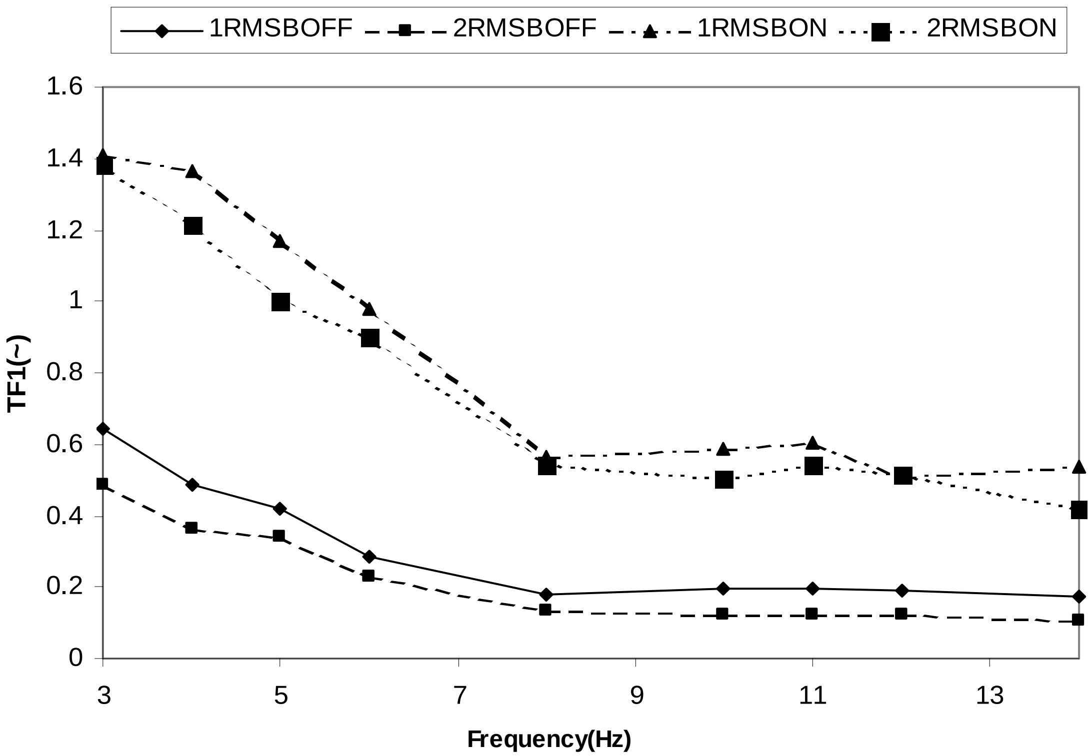


**Figure 3.18: Comparision of TF1 magnitude with BACK-ON and BACK-OFF conditions**

With a backrest condition, vibration induced lumbar rotations (TF2) of the trunk at 2 RMS ($ms^{-2}$) were higher in magnitude (Figure 3.19). With increasing frequency the lumbar rotations to that of seat pan acceleration exhibited a drop in magnitude, suggesting attenuation of the induced vibration during with and without backrest conditions at these frequencies.

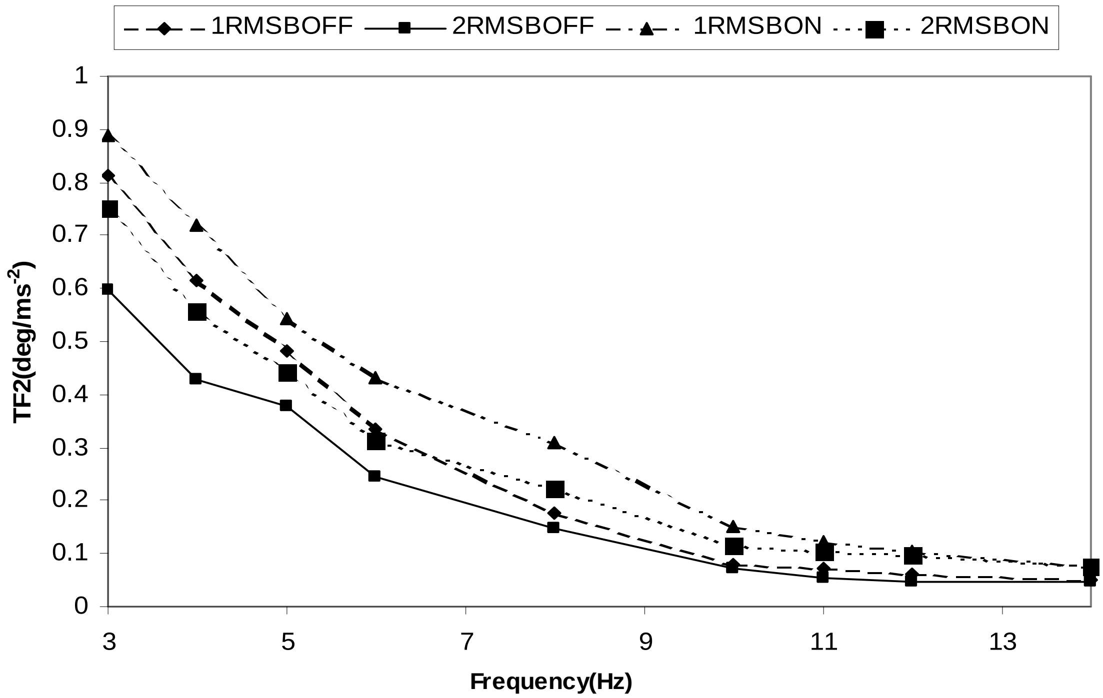


**Figure 3.19: Comparision of TF2 magnitude with BACK-ON & BACK-OFF conditions**

Vibration induced muscle activity transmission mode represented in TF3 exhibited a drop in magnitude with increasing frequency. A peak is exhibited at 5 Hz with 1 RMS ($ms^{-2}$) and at 6 Hz 2 RMS ($ms^{-2}$) vibration magnitudes without the backrest condition. The peak behavior is exhibited at 6 Hz and 8 Hz during 1RMS ($ms^{-2}$) and 2RMS ($ms^{-2}$) magnitudes respectively with a backrest condition (Figure 3.20).

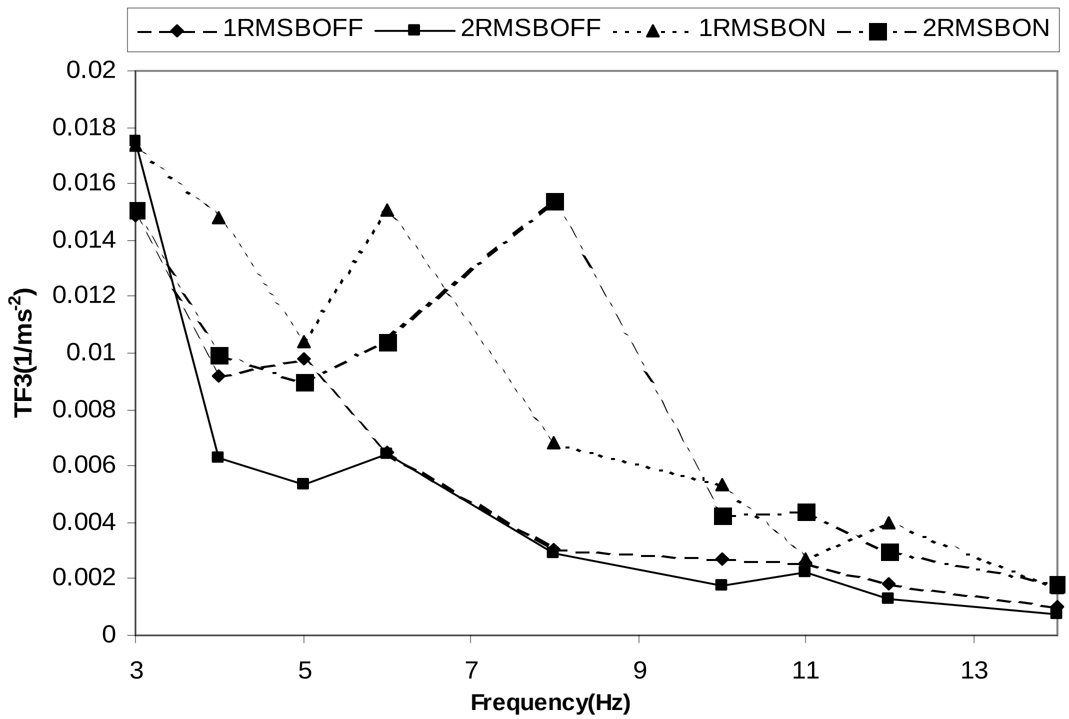


**Figure 3.20: Comparision of TF3 magnitude with BACK-ON & BACK-OFF conditions**

The Neuromotor transmission with and without a backrest conditions exhibited different peaks at different frequencies (Figure 3.21). With a backrest condition MNT exhibited a large peak at 8 Hz, for the 2RMS($ms^{-2}$) magnitude.

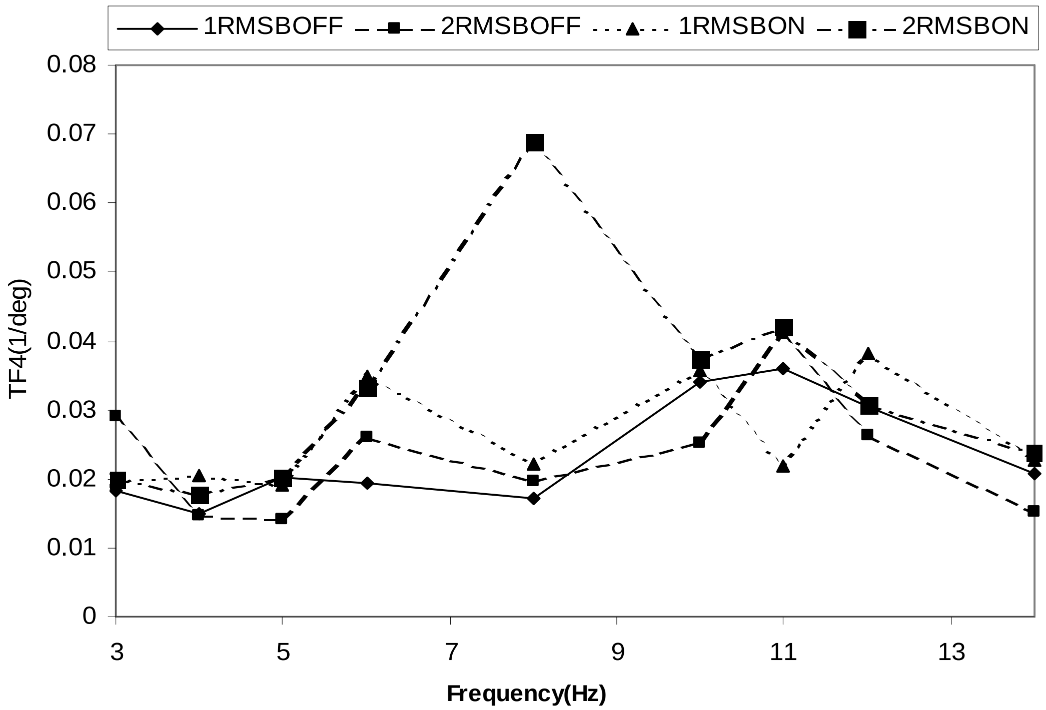


**Figure 3.21: Comparision of TF4 magnitude with BACK-ON & BACK-OFF conditions**

# 4 Discussion

The present study focused on the measurement of vibration response in terms of transmissibility functions. Trunk acceleration transmissibility (TF1), the vibration transmitted to lumbar rotations (TF2), the vibration-induced muscle activity (TF3), and the transmissibility function between lumbar rotations and the paraspinal muscle response (TF4) were assessed. The time delay between the peak occurrence of input to the peak occurrence of output (calculated as time delay and as phase response) of TF3 and TF4 were also investigated. The transmissibility functions (TF1-TF4) were measured both with and without a backrest fixed to the vibrating seatpan. These results demonstrate that human response to WBV in a supported and unsupported seated posture is complex and dependent on both vibration frequency and magnitude.

## 4.0 Trunk acceleration transfer function (TF1)

### 4.0.1 TF1 without a backrest

Trunk acceleration transmissibility function (TF1) was a measure of the ratio of accelerations measured at C-7 of the spinous process to the input seat acceleration. In this study, acceleration was measured at C-7 spinous process as it represents the upper geometrical limit of the trunk. The accelerations measured at C-7 of the spinous process exhibited a decrease in magnitude with increasing in frequency. The seat to trunk acceleration transmissibility ratio exhibited a drop in magnitude from 0.65 at 3 Hz to 0.14 at 14 Hz and did not exhibit resonance or peaking behavior in the investigated frequency span.

The results of TF1 can be compared to literature data on transmission of horizontal seatpan vibration. Griffin et al. [1] measured the transmission of horizontal seat vibration to the head, and found the head motion decreased in magnitude with increasing frequency showing a similar pattern with that of the current study. This study was found to have a similar results despite using a different input seat vibration magnitude $1.75 \pm 0.05$ $ms^{-2}$, and a random vibration as input rather than sinusoidal vibration. The head accelerations in Griffin's study were measured using a bite bar to monitor the motion of the head during fore-and-aft vibration. This method has the advantage of using the rigid skull to be free from the possible effect of skin motion artifact. However, the use of a bite bar doesn't, allow for the characterization of the response dynamics of the spine. In both the current study and Griffin's study the resonance character of the human spine and head was exhibited at very low frequencies in the fore-and-aft seat pan vibration[1]. A resonance peak was observed at 2 Hz by Griffin in the transmission of fore-aft seat pan vibration [1]. In the current study, the frequency range assessed was 3-14 Hz. The shaker specifications constrained the vibrations to frequencies greater than or equal to 3 Hz, restricting the study to frequencies above 3 Hz. As frequencies lower than 3 Hz were not examined, the resonance peak was not observed in the current study. Despite differences in the experimental protocols the transmission patterns exhibited were similar between the current study and literature data.

The measure of trunk acceleration transmissibility (TF1) in the fore-aft direction exhibited quite different transmission characteristics when compared to that of the trunk acceleration transmissibility measured during the vertical seat pan vibration [2]. In literature data on vertical vibration a primary resonance peak at 4 Hz [2] was found.

However, such resonance behavior was not exhibited in the current investigation of fore-aft vibration in the frequency span of 3-14 Hz consistent with other fore-aft vibration studies that found resonance at 2 Hz [1]. A transmissibility function peak of 1.6 is exhibited at the resonance magnitude in the vertical seat pan vibration study [2]. However, the maximum transmissibility ratio of 0.6 was found with the fore-aft vibration in the current study. This would suggest that without a backrest, less vibration is transmitted to the trunk in this frequency range with horizontal than with vertical vibrations. This could be due to attenuation of the vibration by the soft tissues of the buttocks.

### 4.0.2 TF1 with a backrest

The accelerations measured on the C-7 of the spinous process when the subject was supported by the backrest also exhibited a gradual decline in magnitude with increasing frequency. At low frequencies, the transfer function (TF1) exhibited a transmission function magnitude of 1.4 at 3 Hz with a backrest and 0.6 without a backrest. A transmission function magnitude of greater than one was exhibited at several of the lower frequencies (3-6 Hz) suggesting a resonance behavior at these frequencies.

Griffin et al. [1] measured the transmission of horizontal seat vibration to the head with backrest condition, and found a drop in magnitude with increasing frequency. The seat to head transmission[1] in the fore-and-aft vibration with backrest exhibited a primary resonance peak between 1-2 Hz and a secondary peak at 8 Hz unlike the current study. The input vibration in that study was conducted a $1.75 \pm 0.05$ RMS ($ms^{-2}$), random vibration rather than the 1 and 2 RMS ($ms^{-2}$), sinusoidal vibration used in the current study. The accelerations were measured using a bite bar to monitor the motion of the head. The disadvantage in a seat-to-head acceleration transmissibility study is that it cannot characterize the response behavior of the spine. Relative to the trunk, the head can rotate about the cervical vertebrae, altering the linear, horizontal motions of an accelerometer attached to a bite bar. In a separate study the use of a backrest induced greatest head motion in the fore-aft direction between 5 and 10 Hz [4]. In addition, the seat-to-head transmissibility study used a short backrest, unlike the current study [1]. The current study had a high rigid backrest, which provides support for the upper torso or thoracic region. Such differences in the experimental protocols could account for the differences in transmission seen in these studies.

## 4.1 Vibration induced back rotations (TF2)

### 4.1.1 TF2 without a backrest

Both linear and rotational movement of the upper body was observed during fore-and-aft vibration [1,5]. A differential in the linear, fore-aft motion of the thorax relative to the pelvis can lead to a rotational motion of the spine with the horizontal seat pan vibration. These rotational motion or cyclic flexion-extension motions, which were recorded using the lumbar electrogoniometer, exhibited a drop in magnitude with increasing frequency. The spinal flexion corresponded to the posterior (backward) seat acceleration and extension motion corresponded to the anterior (forward) seat acceleration. These cyclic flexion-extension motions exhibited a gradual decline with increasing frequency during the fore-and-aft vibration. With increasing frequency, the vibrations are attenuated by the soft tissues of the buttocks leading both to a drop in linear motion and to a drop in lumbar rotation [6]. Lumbar rotations measured in this study did not exhibit any peaks, suggesting no resonance behavior in the investigated frequency span of 3-14 Hz.

Literature data on vibration-induced, lumbar rotation, transmission characteristics in the vertical seat pan vibration exhibited quite different transmission characteristics when compared to that of transmission characteristics in the fore-and-aft vibration [1]. The lumbar rotations measured in the vertical seat pan vibration exhibited a pronounced peak near the resonance frequency of 4 Hz [2]. However such resonance was not exhibited in the fore-aft direction study. This difference between vertical transmission and horizontal transmission to lumbar rotation is similar to that observed for linear trunk accelerations and suggests that the attenuation characteristics of the soft tissues of the buttocks are different for these two vibration directions.

### 4.1.2 TF2 with a backrest

The lumbar rotations measured with a backrest condition also exhibited a gradual decline in magnitude with increasing frequencies. The backrest can serve as another source of vibration [1,5]. A more pronounced rocking motion of the upper body was observed with a backrest. The use of backrest yielded considerable interactions of the upper body with the backrest, which subsequently induced back rotations during WBV. The backrest restricts the posterior motion of the upper body but not anterior motion resulting in the subject bouncing anteriorly from the backrest at low frequencies. At high frequencies, the vibrations are probably attenuated by soft tissues before reaching the spine leading to a drop in magnitude of lumbar rotations. The responses to horizontal vibration show strong effect of vibration magnitude. The hypothesis that the backrest might reduce the cyclic flexion-extension motion proved to be wrong as greater movement of the upper body is observed particularly at low frequencies. It was speculated that the motion of the thorax would follow the motion of the backrest and the pelvis would follow motion of the seat pan resulting in synchronous movement of the thorax and pelvis and little lumbar rotation. However, at low frequencies the trunk motion (TF1) was greater than one suggesting the thorax was moving more than the pelvis causing lumbar rotations (TF2). At higher frequencies the TF2 exhibited similar transmission both with and without a backrest.

## 4.2 Vibration induced muscle activity (TF3)

### 4.2.1 TF3 without a backrest

Peak-peak nEMG exhibited a peak at 6 Hz, 2 RMS ($ms^{-2}$) vibration magnitude and at 5 Hz for 1 RMS ($ms^{-2}$) intensity. A large drop in magnitude occurred at 3-4 Hz in both the intensities. The higher nEMG measured at lower frequencies was indicative of higher muscle activity, which was required to stabilize the upper body from swaying and rocking motion. The muscle could be acting as a biomechanical feedback element and opposing inertial trunk forces as suggested by Seroussi et al. [7] Muscle activation could also be due to activation of stretch reflexes in the extensor muscles of the trunk such as the erector spinae. Due to attenuation of the soft tissues, the peak-peak nEMG at high frequencies exhibited a relatively low magnitude when compared to those at lower frequencies. The peak of the nEMG transmission (TF3) AT 5-6 Hz was not found in other transmission function and is therefore not a direct result of the lumbar rotations. Since literature studies have demonstrated 4-6 Hz vertical motion resonance with the verical seat pan vibration, the 5-6 Hz peak in the current study might be a result of coupled vertical motion causing additional paraspinal muscle activation.

Several studies have measured the vibration-induced muscle activity with the vertical seat pan vibration [2, 7, 8]. The response of vibration-induced nEMG in the vertical seat pan vibration showed a peak between 4-6 Hz was a result of the higher muscle activity at regions of trunk resonance [2, 7, 8]. However, no study to date has examined vibration-induced muscle activity with horizontal vibration.

### 4.2.2 TF3 with a backrest

Similar to without a backrest, the peak-peak nEMG transmission (TF3) with a backrest exhibited a decrease with increasing frequency but the transmission magnitudes with a backrest were higher. A peak was found at 6 Hz for 1 RMS ($ms^{-2}$) intensity and at 8 Hz for 2 RMS ($ms^{-2}$) intensity at higher frequencies than found without a backrest. Higher EMG measured at low frequencies was indicative of muscle activity, which may result from stabilizing the spine against greater levels of swaying and rocking motion (TF1 and TF2). The hypothesis that the backrest might reduce the trunk rotation, which in turn would reduce peak-peak nEMG magnitude also, was found to be false for both trunk rotations (TF2) and muscle activity (TF3). With the backrest, the muscle activity exhibited peaks at 6-8 Hz, which might be coupled a vertical motion stimulating the neuromotor system, or an external stimulation such as from the backrest which itself could be stimulating the paraspinal muscle further leading to EMG activity. The small peaks at 10-12 Hz might correspond to the internal resonance of the neuromuscular system.

## 4.3 Neuro-motor transmission (TF4)

### 4.3.1 TF4 without a backrest

The transmission function of erector spinae muscles to vibration-induced lumbar rotations (TF4) was relatively constant up to 8 Hz with peak at 11 Hz and a small peak similar to that of TF3 at 5-6 Hz. If lumbar rotations directly influence nEMG during vibration then TF2, and TF3 would exhibit similar characteristics and TF4 would be constant at all frequencies. The peak at 5-6 Hz might be due to coupled vertical motion causing activation of the paraspinal muscles.

The peak exhibited at 11 Hz might correspond to an internal resonance of the neuromuscular system. However, as the vibrations transmitted in the fore-and-aft direction at higher frequencies are attenuated, the lumbar rotations and EMG activity measure may be more susceptible to noise and therefore more difficult to interpret.

When an activated muscle is stretched by an external agency and experiences a length change, a reflex can be activated, resulting in increased activation of the muscle. This is called the stretch reflex. Cyclic variation in the nEMG with vibration can reflect the repetitive muscle activation increase from this stretch reflex activation [7]. Other factors which might affect TF4 include other modes of reflex activation beyond the lumbar rotation, such as internal resonance of the neuromotor feedback loop due to delay in the circuit timing, or non-linearity in the neuromotor response with frequency.

Abraham [2], measured the response of the mechano-neuromotor transmission in a vertical seat pan vibration study and found a double peaked character at 4-6 Hz and 10 Hz. Abraham suggested the peak at 4-6 Hz is a result of the axial vibration resonance or the effect of other response feedback loops such as voluntary control. The study suggested that the second peak at 10 Hz was a result of the internal resonance of the neuromuscular system [2]. Using a simulink model of the neuromotor system Abraham [2], assessed the response of the neuromotor system to sinusoidal input and in particular the effects of a typical stretch reflex delay of 50 ms. He found a resonance between 10-12 Hz suggesting an internal resonance in the neuromotor system at these frequencies with a delayed neuromotor response [2]. The result of the peak at 11 Hz in the TF4 in the current fore-and-aft vibration study appear to correspond to the same internal resonance of the neuromuscular system suggested by Abraham although it might be a noise artifact as peak-peak EMG at these higher frequencies is low.

### 4.3.2 TF4 with a backrest

The mechano-neuromotor transmission (TF4, the ratio of nEMG to lumbar rotation) in the presence of a backrest was relatively constant across frequencies with small peaks at 6, 10 and 12 Hz for 1 RMS ($ms^{-2}$), 11 Hz 2 RMS ($ms^{-2}$) and a larger peak at 8 Hz for 2

RMS ($ms^{-2}$). These peaks at 6 and 8 Hz reflect peaks in the nEMG magnitude (TF3). At frequencies higher than 10 Hz magnitudes of lumbar rotation and nEMG were small making the data at these frequencies more susceptible to noise and prone to error. If the lumbar rotations (TF2) directly influence the muscle activity during vibration, and then TF2 and TF3 would essentially be the same and TF4 would be constant. The peaks at 6 and 8 Hz (2RMS ($ms^{-2}$) relatively high magnitude peak) found, might be a result of coupled vertical motion causing activity in the erector spinae muscles or the result of an external stimulating agent, such as a backrest in this case which could be pressing the paraspinal muscles and causing mechanoreceptor activation. The peaks at 10-12 Hz might correspond to the internal resonance of the neuromuscular system.

## 4.4 Estimated lumbar rotations on bone using correction factor and rotations measured on skin

The electrogoniometer when mounted on the skin tends to over-estimate true spinal angular motion since direct contact with the vertebra is not made. To examine the possible effects of local tissue dynamics on measurement of lumbar rotation by the electrogoniometer a small sub-study was performed. The electrogoniometer was perturbed horizontally relative to the skin and the resulting oscillations were examined. The results of this sub-study were used to create a correction factor that could be applied to the experimental data. The lumbar rotations measured directly with the electrogoniometer and the lumbar rotations calculated with the correction factor were less than 6.8% different, indicating that the correction factor was not necessary at the frequencies examined.

Several other studies have measured the effect of skin artifact of local tissue accelerometer vibration from the surface measurement of the spine both in the vertical and the fore-aft axis [9, 10]. In these studies, a free oscillation test study was conducted in the vertical direction and the responses of the oscillation in the vertical and fore-aft directions were measured [9, 10]. The estimated responses in the fore-aft direction over the spine, as a result of oscillations in the vertical direction, when compared to the measurements on the skin did not require correction. Several other studies estimated the stiffness of tissue on other parts of the body such as the, tibia in the direction perpendicular to the bone and in the direction along the bone [11, 12] .The measured stiffness exhibited, ranged from $1.8 \times 10^3$ to $4.1 \times 10^5$ $Nm^{-1}$ in the normal direction and $4.5 \times 10^2$ to $6.5 \times 10^2$ $Nm^{-1}$ for the shear direction. As the stiffness of tissue in the normal direction was generally much higher than the stiffness in the shear direction, it is reasonable to expect that the correction may be not required in the fore-aft direction.

## 4.5 Delay Times

The measured offset between the maximum peak of the acceleration and maximum peak of the muscle activity (nEMG) exhibited a decline with increasing frequency from 390 ms at 3 Hz to 37 ms at 14 Hz without the backrest and from 363 ms at 3 Hz to 43 ms at 14 Hz with the backrest. It was assumed that peak acceleration was followed by lumbar rotations, which was in turn followed by muscle activation. Based on these assumptions the delays measured in the current study were offset by more than one complete cycle at low frequencies. At the frequencies higher than 10 Hz, magnitudes of both the lumbar rotations and nEMG were small, making the data at these frequencies susceptible to noise and more difficult to interpret. Hence the delay time calculations with in this range are prone to error.

Time delay measured between peak lumbar rotation and peak nEMG activation also exhibited a decrease in magnitude from 184 ms at 3 Hz to 28 ms at 14 Hz without the backrest and 180 ms at 3 Hz to 29 ms at 14 Hz with the backrest. Based on the hypothesis that lumbar rotations induces the EMG activity this suggests that there may be a transition from more polysynaptic reflex that are associated with longer time delays to faster monosynaptic reflex feedback systems. A monosynaptic reflex requires only one synapse to complete the reflex and hence these reflexes are fast with a shorter time delay, and may be more appropriate for response at higher frequencies. Polysynaptic reflexes require more inter-neurons connections between the sensory and motor signals in the central nervous system. Hence a signal would take more time to get transmitted through the neural pathway and arrive at the proper neurons.

Delays measured in previous vertical seat pan vibration studies also exhibited a drop in magnitude with increasing frequency from 230 ms at 3 Hz to 30 ms at 20 Hz in one study from 250 ms at 3 Hz to 130 ms at 10 Hz in another study [2]. The delay time measured between peak lumbar rotations and peak EMG in the first vertical seat pan vibration study also exhibited a decline in magnitude with increase in frequency from 150 ms at 3 Hz to 30 ms at 20 Hz indicating transition from polysynaptic to monosynaptic reflexes [2].

## 4.6 Strengths and limitations

The results presented in this study describe the response characteristics of vibration-induced lumbar rotations and vibration-induced EMG activity and to vibration in the frequency range of 3-14 Hz at two different vibration magnitudes. A few studies have focused on the mechanical transmission of input seat vibration to head in the fore-and-aft direction along with the biodynamic interactions of the seated occupants with the seat-pan and backrest. However, none of the studies have investigated the response characteristics of the muscle activity and lumbar rotations with fore-and-aft vibration. Understanding the transmission of vibration to the neuromotor system is important in assessing possible mechanisms for low back injury. Muscle fatigue and neuromotor habituation have both been suggested to be effects of whole body vibration [13, 14]. By understanding transmission characteristics it is possible to identify the vibration directions, frequencies and magnitudes that may cause the greatest effects.

While providing interesting results, this study has a few limitations. In this study, a high, rigid backrest was examined. However, in industry a number of different backrest styles exist that should also be examined such as a low backrest, or an inclined backrest. In addition, this study examined only constant frequency, sinusoidal vibration. Vibrations that are random or a mixture of frequencies might elicit different responses from the neuromotor system. Finally, longer durations of exposure may alter the neuromotor response.

## 4.7 Implications

The detrimental effect of the backrest on the transmission of vibration in the fore-and-aft direction might be an important consideration in the design of vibration isolators for vehicle seats particularly in trucks. It may be important to use lower backrests or backrests that have been vibration isolated to prevent the increased horizontal vibration transmission seen in this study. In addition, vehicles with significant horizontal vibration should contain low frequency (< 4 Hz) isolation, as horizontal transmission is greatest at these frequencies.

Unlike previous studies of vertical vibration, a current study in our laboratory has not found any post-vibration effect on dynamic trunk response or position sense with fore-and-aft vibration at 5 Hz, 1RMS ($ms^{-2}$) vibration for 20 minutes without a backrest support [15]. The error in a reposition test did not exhibit a significant change after the vibration although such patterns have been observed with vertical vibration. From the current study, the transmission of horizontal vibration at 5 Hz was found to be lower than with vertical vibration suggesting less vibration is transmitted to the neuromotor system. Given this reduced transmission, it is not surprising that vibration-induced neuromotor effects were not observed. Future studies of the effects of horizontal vibration should be conducted at lower frequencies or in conditions with a backrest where there will be greater delivery of vibration to the musculature.

## 4.8 Future Work

Other frequencies and transmission models may also be problematic and needs to be studied. In this experiment a short exposure for a period of 40 sec during each trial was conducted. Longer vibration exposures such as those observed in the normal working day may have different effects. Neuromotor response to vibration may change over time with proprioceptive loss and muscle fatigue. Altered sitting postures may cause changes in the resonance behavior, and neuromotor transmission of the subject. EMG data collected on muscle groups such as RA, IO, and EO can also be processed to analyze the neuromotor transmission to these muscles. Finally, the response characteristics of the fore-and-aft seat pan vibration with short, inclined and other backrest orientations also need to be investigated.

## 4.9 Conclusions

Despite the importance of fore-and-aft vibration, transmission characteristics were not extensively investigated in the past. Several studies have examined biodynamic interactions of the seated occupants with the seat-pan and backrest in the fore-and-aft vibration. Transmission of vibration to the neuromotor system is important in assessing possible mechanisms for low back injury. The current study examined the mechanical transmission function (Trunk acceleration transmissibility, Vibration-induced lumbar rotation) including the neuromotor transmissibility (vibration induced lumbar rotation to erector spinae muscle activity) were quantified for a frequency range of 3-14 Hz at two different vibration magnitudes and with two seating conditions (with and without backrest). The results exhibited quite different transmission characteristics when compared to that of vertical seat pan vibration transmission. The mechanical transmission functions (TF1, TF2) did not exhibit any resonance phenomena without the backrest. However, the transmission function magnitude with the backrest exhibited a ratio greater than one indicating the resonance phenomena. Mechano-neuromotor transmission without the backrest exhibited a double peaked trend with a primary peak at 5-6 Hz and a secondary peak at 11 Hz. The primary peak at 5-6 Hz might be a result of coupled vertical motion causing the muscle activity. The secondary peak at 11 Hz might correspond to the internal resonance of the neuromotor system. Mechano-neuromotor transmission with the backrest exhibited a relatively constant transmissibility, with small peaks at 6, 10 and 12 Hz for 1 RMS ($ms^{-2}$) and a larger peak at 8 Hz for 2 RMS ($ms^{-2}$). The peaks at 6 and 8 Hz might be a result of coupled vertical motion. The small peaks at 10-12 Hz might correspond to the internal resonance of the neuromuscular system. Future work should include other frequencies and transmission models including real time and longer duration of exposure.

## 4.10 References


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# 5 Appendix A

## 5.0 Subject Data with a backrest

**KEY:** **Frequency** ⟶ **Hz (3, 4, 5, 6, 8, 10, 11, 12, 14)**

**TF1=** ($acceleration_{spine}$)/ ($acceleration_{seat}$)

**TF2=** (*Lumbar rotations)/* ($acceleration_{seat}$)

**TF3=** *(nEMG)/* ($acceleration_{seat}$)

**TF4**= *(nEMG)/ (Lumbar rotations)*

**Subject #1**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 1.243299 | 1.386392 | 2.145684 | 1.6030739 | 0.0165954 | 0.0143225 | 0.0077343 | 0.0089344 |
| **4** | 0.666414 | 1.382907 | 2.310869 | 1.6052645 | 0.037356 | 0.014494 | 0.0161654 | 0.00902902 |
| **5** | 0.760722 | 0.741418 | 0.950467 | 0.8188069 | 0.0187475 | 0.0251773 | 0.0197245 | 0.0307488 |
| **6** | 0.770391 | 0.927911 | 0.73072 | 0.5414268 | 0.078779 | 0.0600606 | 0.1078102 | 0.11093015 |
| **8** | 0.33271 | 0.321347 | 0.664919 | 0.5008931 | 0.0058452 | 0.0951401 | 0.0087909 | 0.18994091 |
| **10** | 0.686413 | 0.352986 | 0.45449 | 0.3080483 | 0.0083024 | 0.0201378 | 0.0182676 | 0.0653722 |
| **11** | 0.838526 | 0.838222 | 0.237553 | 0.2303327 | 0.0069351 | 0.0277841 | 0.0291939 | 0.1206258 |
| **12** | 0.294198 | 0.639715 | 0.181549 | 0.2443387 | 0.0182535 | 0.0153758 | 0.100543 | 0.06292808 |
| **14** | 1.114237 | 0.689206 | 0.085626 | 0.1969359 | 0.0029055 | 0.0069116 | 0.0339321 | 0.03509547 |

**Subject #2**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 1.460969 | 1.691348 | 0.520457 | 0.2367065 | 0.0181117 | 0.0123455 | 0.0347996 | 0.0521553 |
| **4** | 0.986277 | 1.249557 | 0.313764 | 0.2640506 | 0.0084966 | 0.0108496 | 0.0270795 | 0.04108902 |
| **5** | 0.874432 | 0.854713 | 0.279905 | 0.1478672 | 0.0072607 | 0.0064202 | 0.0259401 | 0.04341884 |
| **6** | 0.933404 | 0.766045 | 0.209683 | 0.1532616 | 0.0055116 | 0.0040238 | 0.0262852 | 0.02625467 |
| **8** | 0.594978 | 0.556287 | 0.147165 | 0.1343174 | 0.0074036 | 0.0059411 | 0.050308 | 0.04423165 |
| **10** | 0.548047 | 0.446121 | 0.107118 | 0.0986454 | 0.0054047 | 0.0020528 | 0.0504561 | 0.02081034 |
| **11** | 0.383112 | 0.379391 | 0.129699 | 0.1329085 | 0.0020884 | 0.0012963 | 0.0161019 | 0.0175323 |
| **12** | 0.412965 | 0.408402 | 0.130768 | 0.1168628 | 0.002196 | 0.0010628 | 0.0167928 | 0.00909456 |
| **14** | 0.446062 | 0.421884 | 0.12572 | 0.1064314 | 0.0013148 | 0.0009328 | 0.0104582 | 0.00876411 |

**Subject #3**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| Hz | 1RMS | 2RMS | 1RMS | 2RMS | 1RMS | 2RMS | 1RMS | 2RMS |
| 3 | 2.040714 | 1.175983 | 0.941048 | 1.0338802 | 0.0089845 | 0.0172568 | 0.0095474 | 0.01669132 |
| 4 | 2.034997 | 0.890596 | 0.660958 | 0.5834875 | 0.0026509 | 0.0039519 | 0.0040106 | 0.00677287 |
| 5 | 1.525097 | 1.057693 | 0.429084 | 0.4024503 | 0.0032207 | 0.0031822 | 0.007506 | 0.00790701 |
| 6 | 0.95854 | 0.777339 | 0.254867 | 0.2249339 | 0.0017009 | 0.0017276 | 0.0066738 | 0.0076806 |
| 8 | 0.573005 | 0.613713 | 0.100645 | 0.108812 | 0.0033751 | 0.0021321 | 0.0335347 | 0.01959402 |
| 10 | 0.79256 | 0.611584 | 0.042498 | 0.059099 | 0.0001508 | 0.0002481 | 0.0035489 | 0.00419837 |
| 11 | 0.733779 | 0.594182 | 0.034293 | 0.0536107 | 0.0003016 | 0.0002497 | 0.0087953 | 0.0096575 |
| 12 | 0.682527 | 0.566127 | 0.027193 | 0.0452528 | 0.0009409 | 0.0001324 | 0.0346021 | 0.00292481 |
| 14 | 0.528072 | 0.436938 | 0.052823 | 0.0520403 | 0.0001661 | 0.0002377 | 0.0031451 | 0.0045676 |

**Subject #4**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| Hz | 1RMS | 2RMS | 1RMS | 2RMS | 1RMS | 2RMS | 1RMS | 2RMS |
| 3 | 1.978975 | 1.586099 | 0.793983 | 0.7620094 | 0.0354686 | 0.0486907 | 0.0446717 | 0.06389776 |
| 4 | 0.97789 | 1.080737 | 0.432487 | 0.3021513 | 0.0199431 | 0.0159299 | 0.0461126 | 0.05272147 |
| 5 | 0.935682 | 0.793435 | 0.314526 | 0.2157157 | 0.0045275 | 0.0010958 | 0.0143946 | 0.00507992 |
| 6 | 0.741701 | 0.636248 | 0.309801 | 0.2226534 | 0.0014683 | 0.0010431 | 0.0047396 | 0.004685 |
| 8 | 0.329031 | 0.324733 | 0.282626 | 0.2121469 | 0.005591 | 0.0172947 | 0.0197824 | 0.08152241 |
| 10 | 0.432375 | 0.42199 | 0.212907 | 0.2032739 | 0.0001017 | 5.786E-05 | 0.0004777 | 0.00028465 |
| 11 | 0.513474 | 0.403449 | 0.203176 | 0.1598328 | 7.904E-05 | 0.0001084 | 0.000389 | 0.0067818 |
| 12 | 0.499832 | 0.513572 | 0.142054 | 0.1387998 | 3.603E-05 | 5.686E-05 | 0.0002537 | 0.00040967 |
| 14 | 0.579703 | 0.557781 | 0.023947 | 0.0264359 | 0.0002837 | 0.0001386 | 0.0118457 | 0.00524099 |

**Subject #5**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| Hz | 1RMS | 2RMS | 1RMS | 2RMS | 1RMS | 2RMS | 1RMS | 2RMS |
| 3 | 1.61733 | 2.438939 | 1.009359 | 0.7879121 | 0.0326217 | 0.0244563 | 0.0323192 | 0.03103944 |
| 4 | 1.388668 | 1.512144 | 0.372692 | 0.2998905 | 0.0089809 | 0.0137229 | 0.0240974 | 0.04575971 |
| 5 | 0.932455 | 0.709521 | 0.601174 | 0.4856481 | 0.0054878 | 0.0062205 | 0.0091285 | 0.01280872 |
| 6 | 1.165032 | 1.044022 | 0.591258 | 0.4509888 | 0.0046687 | 0.0039884 | 0.017896 | 0.00884371 |
| 8 | 0.25274 | 0.227757 | 0.363731 | 0.2792665 | 0.0017613 | 0.0031626 | 0.0048422 | 0.01132462 |
| 10 | 0.23218 | 0.174862 | 0.107147 | 0.1253562 | 0.0015256 | 0.0010831 | 0.0112381 | 0.00864017 |
| 11 | 0.3476 | 0.328888 | 0.087952 | 0.1138329 | 0.0008282 | 0.000961 | 0.0094162 | 0.02084649 |
| 12 | 0.240461 | 0.240918 | 0.0429 | 0.053496 | 0.0016372 | 0.0011152 | 0.038162 | 0.0084494 |
| 14 | 0.275513 | 0.209675 | 0.027959 | 0.0462216 | 0.0016915 | 0.0007794 | 0.0604982 | 0.01686217 |

**Subject #6**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 1.418071 | 1.296465 | 0.592603 | 0.2570837 | 1.25E-03 | 1.68E-03 | 2.11E-03 | 6.52E-03 |
| **4** | 1.774357 | 1.439877 | 0.52749 | 0.2997126 | 1.64E-03 | 8.36E-04 | 3.11E-03 | 2.79E-03 |
| **5** | 1.352965 | 1.350472 | 0.523268 | 0.3520181 | 1.71E-03 | 3.49E-04 | 3.26E-03 | 9.92E-04 |
| **6** | 0.927852 | 0.923083 | 0.539055 | 0.3654412 | 1.75E-03 | 6.45E-04 | 3.25E-03 | 1.76E-03 |
| **8** | 0.43024 | 0.534989 | 0.433852 | 0.2886898 | 1.78E-04 | 3.00E-04 | 4.11E-04 | 1.04E-03 |
| **10** | 0.718638 | 0.562385 | 0.197893 | 0.1405126 | 8.48E-04 | 4.85E-04 | 4.29E-03 | 3.45E-03 |
| **11** | 0.512225 | 0.445561 | 0.15934 | 0.1168138 | 5.31E-04 | 1.86E-04 | 3.33E-03 | 1.59E-03 |
| **12** | 0.634276 | 0.530971 | 0.053638 | 0.0777723 | 6.63E-04 | 3.40E-04 | 1.24E-02 | 4.37E-03 |
| **14** | 0.412449 | 0.380934 | 0.041763 | 0.0410943 | 4.34E-04 | 2.55E-04 | 1.04E-02 | 6.21E-03 |

**Subject #7**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 1.023588 | 1.441184 | 1.114204 | 0.8906834 | 0.0086215 | 0.018479 | 0.0077378 | 0.02074696 |
| **4** | 1.506556 | 1.54686 | 0.963338 | 0.7058171 | 0.0097558 | 0.0081589 | 0.0101271 | 0.01155947 |
| **5** | 1.456274 | 1.359986 | 1.076009 | 1.2545108 | 0.0087957 | 0.0078166 | 0.0081744 | 0.00623077 |
| **6** | 1.367042 | 1.429501 | 0.15025 | 0.2076727 | 0.0059882 | 0.0030076 | 0.0398551 | 0.01448249 |
| **8** | 0.793039 | 0.910842 | 0.254906 | 0.188172 | 0.0136569 | 0.0073387 | 0.053576 | 0.03899991 |
| **10** | 1.046166 | 0.907626 | 0.021974 | 0.0351239 | 0.0067512 | 0.0034002 | 0.061225 | 0.09680496 |
| **11** | 1.099557 | 0.967978 | 0.143019 | 0.1283402 | 0.0077326 | 0.0043011 | 0.0540667 | 0.03351366 |
| **12** | 0.963699 | 0.955054 | 0.12874 | 0.1158343 | 0.0064454 | 0.004585 | 0.0500649 | 0.03958211 |
| **14** | 0.685636 | 0.620942 | 0.121391 | 0.0940174 | 0.0045433 | 0.0025276 | 0.0374272 | 0.02688465 |

**Subject #8**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 1.265788 | 1.534821 | 0.347063 | 0.1794273 | 0.0190029 | 0.0142843 | 0.0547535 | 0.07961059 |
| **4** | 1.334062 | 1.504187 | 0.489016 | 0.3384251 | 0.0187034 | 0.0075467 | 0.0382471 | 0.02229938 |
| **5** | 1.732231 | 1.169726 | 0.312162 | 0.2225501 | 0.0109674 | 0.0063695 | 0.0351337 | 0.02862066 |
| **6** | 1.539082 | 1.4135 | 0.25817 | 0.2144218 | 0.013323 | 0.0045119 | 0.0516056 | 0.02104224 |
| **8** | 0.70699 | 0.824429 | 0.088633 | 0.0891306 | 0.0075257 | 0.007067 | 0.0849092 | 0.07928772 |
| **10** | 0.705373 | 0.662187 | 0.114583 | 0.1359343 | 0.0032413 | 0.0012864 | 0.0282881 | 0.00946333 |
| **11** | 0.575542 | 0.607859 | 0.112246 | 0.1130826 | 0.0006719 | 0.0005561 | 0.0059862 | 0.0049173 |
| **12** | 0.56235 | 0.47924 | 0.229384 | 0.1538956 | 0.0023352 | 0.0009479 | 0.0101803 | 0.00615926 |
| **14** | 0.399744 | 0.476101 | 0.154671 | 0.0713755 | 0.0017152 | 0.0013859 | 0.0110894 | 0.01941748 |

**Subject #9**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 1.536831 | 1.605656 | 0.256947 | 0.3687503 | 0.00345 | 0.006549 | 0.0134269 | 0.01776011 |
| **4** | 1.553487 | 1.892869 | 0.206047 | 0.1977313 | 0.0067776 | 0.0067502 | 0.0328937 | 0.03413822 |
| **5** | 1.307018 | 1.558661 | 0.283723 | 0.152772 | 0.0015595 | 0.0031623 | 0.0054964 | 0.02069942 |
| **6** | 1.085609 | 1.131387 | 0.338262 | 0.1832393 | 0.0026207 | 0.0017574 | 0.077475 | 0.00959079 |
| **8** | 1.184193 | 1.316198 | 0.204395 | 0.141521 | 0.0046157 | 0.0034653 | 0.0225822 | 0.02448591 |
| **10** | 0.574367 | 0.499839 | 0.052382 | 0.0377108 | 0.0012687 | 0.00124 | 0.0242192 | 0.03288288 |
| **11** | 0.873606 | 0.677067 | 0.054492 | 0.052362 | 0.0009321 | 0.0010445 | 0.0171045 | 0.01994852 |
| **12** | 0.515409 | 0.538017 | 0.050249 | 0.0553315 | 0.0002523 | 0.000593 | 0.0050215 | 0.01071647 |
| **14** | 0.606411 | 0.581112 | 0.06173 | 0.0703758 | 0.0008039 | 0.0005922 | 0.0130222 | 0.00841548 |

**Subject #10**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 1.307148 | 0.880573 | 0.63032 | 0.3192491 | 0.0229358 | 0.0182054 | 0.0363875 | 0.05702555 |
| **4** | 1.341855 | 0.395618 | 0.619009 | 0.3919045 | 0.0058061 | 0.0032802 | 0.0093797 | 0.0083698 |
| **5** | 1.283845 | 1.251596 | 0.766234 | 0.5391829 | 0.013986 | 0.0065193 | 0.0182529 | 0.01209115 |
| **6** | 0.824158 | 0.992916 | 0.546836 | 0.4934858 | 0.0104225 | 0.0055094 | 0.0190596 | 0.01116427 |
| **8** | 0.585133 | 0.480457 | 0.421023 | 0.271986 | 0.0131181 | 0.0055091 | 0.0311576 | 0.0202552 |
| **10** | 0.497894 | 0.622833 | 0.057204 | 0.0568446 | 0.0085908 | 0.0045591 | 0.0157067 | 0.08020274 |
| **11** | 0.634515 | 0.587934 | 0.048562 | 0.0733484 | 0.0039465 | 0.0023606 | 0.0812672 | 0.03218391 |
| **12** | 0.661115 | 0.543026 | 0.123053 | 0.1037517 | 0.0041804 | 0.001713 | 0.0339726 | 0.0165102 |
| **14** | 0.576314 | 0.435788 | 0.071989 | 0.090711 | 0.0020453 | 0.0014018 | 0.0284117 | 0.01545336 |

**Subject #11**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 1.531089 | 0.788442 | 1.110764 | 0.787283 | 0.0163577 | 0.0144021 | 0.0147265 | 0.01829344 |
| **4** | 1.554501 | 0.307492 | 0.602275 | 0.3793999 | 0.0048254 | 0.0146329 | 0.0080119 | 0.03856859 |
| **5** | 0.981005 | 0.277147 | 0.374385 | 0.3363311 | 0.0110449 | 0.0097299 | 0.0295013 | 0.02892941 |
| **6** | 0.839812 | 0.432955 | 0.326581 | 0.2035132 | 0.0077813 | 0.0072978 | 0.0238266 | 0.03585893 |
| **8** | 0.319736 | 0.302216 | 0.296259 | 0.1663926 | 0.0130279 | 0.0086977 | 0.0439747 | 0.05227226 |
| **10** | 0.328067 | 0.270928 | 0.263183 | 0.1052293 | 0.0019918 | 0.0018283 | 0.007568 | 0.01737452 |
| **11** | 0.311825 | 0.244916 | 0.185133 | 0.0801408 | 0.0019822 | 0.001367 | 0.010707 | 0.01705757 |
| **12** | 0.224789 | 0.243554 | 0.152862 | 0.0677402 | 0.001169 | 0.0008026 | 0.0076473 | 0.01184774 |
| **14** | 0.308627 | 0.202595 | 0.078697 | 0.0585453 | 0.000757 | 0.0007027 | 0.0096196 | 0.01200234 |

**Subject #12**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 0.681714 | 1.403941 | 2.518092 | 1.6186774 | 0.0286129 | 0.0147268 | 0.0113629 | 0.00909806 |
| **4** | 0.678012 | 1.406079 | 2.358345 | 1.6216457 | 0.0399342 | 0.0149529 | 0.0169332 | 0.00922083 |
| **5** | 0.775454 | 0.752198 | 0.96843 | 0.8308461 | 0.0199075 | 0.0260354 | 0.0205565 | 0.03133601 |
| **6** | 0.782136 | 0.946013 | 0.741065 | 0.5523669 | 0.0812714 | 0.0620601 | 0.1096684 | 0.112353 |
| **8** | 0.337335 | 0.322231 | 0.671509 | 0.5012594 | 0.0063217 | 0.0960753 | 0.0094141 | 0.1916678 |
| **10** | 0.688313 | 0.354822 | 0.456252 | 0.311805 | 0.0086882 | 0.0207091 | 0.0120426 | 0.0664168 |
| **11** | 0.843608 | 0.840219 | 0.239214 | 0.2313647 | 0.0073119 | 0.0281291 | 0.0305664 | 0.12157895 |
| **12** | 0.30072 | 0.64557 | 0.18558 | 0.2445688 | 0.0186133 | 0.0156571 | 0.1002983 | 0.06401939 |
| **14** | 1.138855 | 0.690746 | 0.087692 | 0.1972889 | 0.0029891 | 0.0070566 | 0.0340864 | 0.03576791 |

**Subject #13**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 1.377891 | 1.982923 | 0.311875 | 0.4890754 | 0.0097159 | 0.0066716 | 0.0311533 | 0.01364134 |
| **4** | 1.532002 | 1.920179 | 0.343337 | 0.1922272 | 0.007869 | 0.0073838 | 0.0229192 | 0.03841207 |
| **5** | 1.626085 | 1.673392 | 0.353206 | 0.1962748 | 0.006367 | 0.0070122 | 0.0180262 | 0.03572655 |
| **6** | 1.48219 | 1.474328 | 0.272986 | 0.2383935 | 0.0036307 | 0.0041208 | 0.0132998 | 0.01728584 |
| **8** | 1.060929 | 1.078296 | 0.218157 | 0.1761949 | 0.0032033 | 0.0032477 | 0.0146836 | 0.0184323 |
| **10** | 0.939353 | 1.102749 | 0.170986 | 0.1481274 | 0.0024379 | 0.0013043 | 0.0142578 | 0.00880503 |
| **11** | 0.556289 | 0.66629 | 0.231251 | 0.1538896 | 0.0012189 | 0.0017789 | 0.0052709 | 0.01155941 |
| **12** | 0.792036 | 0.774039 | 0.111745 | 0.1139128 | 0.0006795 | 0.0010264 | 0.0060809 | 0.02901036 |
| **14** | 0.72175 | 0.631881 | 0.082592 | 0.0615199 | 0.0009439 | 0.000695 | 0.0114286 | 0.01129788 |

**Subject #14**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 1.688378 | 1.718433 | 0.276642 | 0.2915031 | 0.0240064 | 0.0065759 | 0.0867778 | 0.02255847 |
| **4** | 1.408931 | 1.186194 | 0.202877 | 0.1417828 | 0.0308598 | 0.0075538 | 0.1521105 | 0.05327725 |
| **5** | 0.778636 | 0.60259 | 0.173326 | 0.1176202 | 0.0254796 | 0.0195836 | 0.1470037 | 0.16649878 |
| **6** | 0.625808 | 0.466563 | 0.138702 | 0.0922437 | 0.0024073 | 0.0048991 | 0.0173562 | 0.05311049 |
| **8** | 0.22217 | 0.178923 | 0.083864 | 0.0500679 | 0.0125096 | 0.009409 | 0.0491647 | 0.18792402 |
| **10** | 0.224387 | 0.2565 | 0.020087 | 0.0354324 | 0.0052402 | 0.006714 | 0.2608696 | 0.18948891 |
| **11** | 0.235053 | 0.229483 | 0.037469 | 0.0332699 | 0.0037879 | 0.0032336 | 0.1010929 | 0.1971335 |
| **12** | 0.150991 | 0.231236 | 0.028022 | 0.0308558 | 0.0020871 | 0.0019382 | 0.0744811 | 0.06281548 |
| **14** | 0.280821 | 0.195405 | 0.022804 | 0.0235391 | 0.0015954 | 0.0010793 | 0.0699613 | 0.04585153 |

**Subject #15**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 0.967338 | 0.908761 | 0.452692 | 0.7087545 | 0.0285485 | 0.0136224 | 0.0630637 | 0.01922017 |
| **4** | 0.911839 | 0.544935 | 0.407082 | 0.3940287 | 0.0154943 | 0.0065138 | 0.0380617 | 0.01653138 |
| **5** | 0.282995 | 0.519604 | 0.293011 | 0.2738789 | 0.0078654 | 0.0071148 | 0.0268434 | 0.02597805 |
| **6** | 0.613609 | 0.45959 | 0.241378 | 0.1501149 | 0.0036756 | 0.0025859 | 0.0152278 | 0.01722585 |
| **8** | 0.26768 | 0.463182 | 0.119657 | 0.1509348 | 0.0063904 | 0.002531 | 0.034306 | 0.01676914 |
| **10** | 0.267094 | 0.340053 | 0.066385 | 0.0622572 | 0.0018225 | 0.0021734 | 0.027453 | 0.03490929 |
| **11** | 0.81615 | 0.532278 | 0.048845 | 0.0406654 | 0.0015987 | 0.0013129 | 0.0327298 | 0.03228547 |
| **12** | 0.671921 | 0.50811 | 0.037018 | 0.0513637 | 0.0032673 | 0.0017047 | 0.0882621 | 0.04818807 |
| **14** | 0.406461 | 0.223561 | 0.02048 | 0.0309275 | 0.0005726 | 0.0023277 | 0.0279605 | 0.07526287 |

**Subject #16**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 1.860181 | 0.507048 | 0.232361 | 0.4449023 | 0.018716 | 0.0153622 | 0.0805469 | 0.03452928 |
| **4** | 1.696893 | 0.324834 | 0.491067 | 0.1372633 | 0.0095748 | 0.0050324 | 0.0194979 | 0.03666238 |
| **5** | 1.10324 | 0.212163 | 0.207952 | 0.2872605 | 0.0120942 | 0.006865 | 0.0581588 | 0.02389813 |
| **6** | 0.565566 | 0.332858 | 0.16835 | 0.0381985 | 0.0174734 | 0.0121332 | 0.103792 | 0.31763661 |
| **8** | 0.236175 | 0.1928 | 0.210203 | 0.070068 | 0.0052476 | 0.0096836 | 0.0249644 | 0.13820359 |
| **10** | 0.272204 | 0.272939 | 0.080947 | 0.1087235 | 0.0039502 | 0.0027493 | 0.0348003 | 0.025287 |
| **11** | 0.292171 | 0.297825 | 0.091147 | 0.0838659 | 0.0024432 | 0.0023706 | 0.0268057 | 0.0282671 |
| **12** | 0.357085 | 0.25974 | 0.097612 | 0.0666232 | 0.0020407 | 0.0030509 | 0.0209059 | 0.04579367 |
| **14** | 0.255743 | 0.249583 | 0.043981 | 0.0262379 | 0.0015957 | 0.0016335 | 0.0362812 | 0.06225681 |

**Subject #17**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 1.264155 | 1.360865 | 1.116723 | 1.244539 | 0.0047685 | 0.0221787 | 0.0042701 | 0.01782079 |
| **4** | 1.396746 | 1.503635 | 0.584014 | 0.9246405 | 0.0124824 | 0.0140452 | 0.0213735 | 0.01518992 |
| **5** | 1.360296 | 1.593706 | 0.787581 | 0.5150038 | 0.0089179 | 0.0070018 | 0.0113232 | 0.01359559 |
| **6** | 1.155631 | 1.428331 | 0.835744 | 0.5626492 | 0.0082952 | 0.0072414 | 0.0099255 | 0.01287016 |
| **8** | 0.838521 | 0.678269 | 0.375174 | 0.294547 | 0.0051411 | 0.0065527 | 0.0137032 | 0.0222467 |
| **10** | 0.653236 | 0.71513 | 0.095671 | 0.075129 | 0.0041854 | 0.0036421 | 0.023748 | 0.04847826 |
| **11** | 0.702895 | 0.697488 | 0.056623 | 0.0732747 | 0.0029164 | 0.0027552 | 0.0515068 | 0.05760072 |
| **12** | 0.93665 | 1.041057 | 0.071108 | 0.0755378 | 0.0065643 | 0.0050887 | 0.0923145 | 0.06736658 |
| **14** | 0.702609 | 0.250093 | 0.106498 | 0.0999357 | 0.0041739 | 0.0027261 | 0.0391924 | 0.02727889 |

**Subject #18**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 1.279453 | 0.963762 | 1.409958 | 1.1976277 | 0.0271479 | 0.0190358 | 0.0192544 | 0.01589457 |
| **4** | 1.510674 | 1.222307 | 0.833689 | 0.75604 | 0.025458 | 0.02486 | 0.0305366 | 0.03288185 |
| **5** | 1.413942 | 1.064196 | 0.707728 | 0.6249083 | 0.0233547 | 0.010666 | 0.0329995 | 0.01706803 |
| **6** | 1.109072 | 0.674574 | 0.579741 | 0.4131925 | 0.0267602 | 0.0032531 | 0.0461589 | 0.00787306 |
| **8** | 0.822555 | 0.337681 | 0.522145 | 0.3305071 | 0.0034611 | 0.0060539 | 0.0066286 | 0.01831706 |
| **10** | 0.799422 | 0.445713 | 0.28207 | 0.0922176 | 0.0298782 | 0.0041994 | 0.1059248 | 0.04553801 |
| **11** | 0.486988 | 0.248186 | 0.22008 | 0.0667391 | 0.0030157 | 0.0011204 | 0.0137028 | 0.05678719 |
| **12** | 0.135579 | 0.099523 | 0.116608 | 0.0561179 | 0.0024133 | 0.0009673 | 0.0206956 | 0.05823607 |
| **14** | 0.146267 | 0.087615 | 0.063504 | 0.0493527 | 0.001424 | 0.0015417 | 0.0224239 | 0.03123891 |

**Subject #19**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 1.355331 | 1.589282 | 1.038525 | 1.1475413 | 0.0101551 | 0.012396 | 0.0097784 | 0.01080218 |
| **4** | 1.527911 | 1.622408 | 0.921928 | 0.9327473 | 0.0173893 | 0.0105358 | 0.0188619 | 0.01129541 |
| **5** | 1.615995 | 1.373905 | 0.895999 | 0.5529474 | 0.0063113 | 0.0082507 | 0.0070439 | 0.01492123 |
| **6** | 1.002207 | 0.639643 | 0.977616 | 0.6047561 | 0.0095982 | 0.0056825 | 0.009818 | 0.00939636 |
| **8** | 0.760815 | 0.52913 | 0.419257 | 0.3120007 | 0.0119402 | 0.008556 | 0.0284794 | 0.02742291 |
| **10** | 0.644199 | 0.468075 | 0.103487 | 0.0778658 | 0.006318 | 0.0024037 | 0.0610513 | 0.03086957 |
| **11** | 0.741967 | 0.698176 | 0.062447 | 0.0768186 | 0.0027032 | 0.0020116 | 0.0432877 | 0.04618621 |
| **12** | 0.595247 | 0.51868 | 0.077526 | 0.0785675 | 0.0010615 | 0.0003952 | 0.0136926 | 0.03803062 |
| **14** | 0.663601 | 0.657562 | 0.116467 | 0.1017709 | 0.0015907 | 0.0015347 | 0.013658 | 0.01507963 |

## 5.1 Subject data without a backrest

**Subject #1**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 0.760985 | 0.697724 | 1.802592 | 1.340523 | 0.011147 | 0.009487 | 0.006184 | 0.007077 |
| **4** | 0.449295 | 0.374876 | 1.000889 | 0.776021 | 0.006486 | 0.003861 | 0.00648 | 0.004975 |
| **5** | 0.313102 | 0.227222 | 0.779513 | 0.642977 | 0.012931 | 0.004079 | 0.016589 | 0.006344 |
| **6** | 0.163818 | 0.095409 | 0.281959 | 0.136518 | 0.011628 | 0.006196 | 0.041238 | 0.045387 |
| **8** | 0.172031 | 0.134932 | 0.33106 | 0.314244 | 0.005712 | 0.003282 | 0.017254 | 0.010445 |
| **10** | 0.151154 | 0.078296 | 0.154983 | 0.10394 | 0.001084 | 0.003717 | 0.006996 | 0.035761 |
| **11** | 0.148175 | 0.066374 | 0.102168 | 0.062348 | 0.002093 | 0.005737 | 0.020484 | 0.092018 |
| **12** | 0.139256 | 0.076386 | 0.15591 | 0.071114 | 0.002354 | 0.002314 | 0.015101 | 0.032542 |
| **14** | 0.143781 | 0.07698 | 0.067207 | 0.07691 | 0.000213 | 0.001245 | 0.003175 | 0.016184 |

**Subject #2**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 0.418222 | 0.396311 | 0.446599 | 0.319048 | 0.022876 | 0.014677 | 0.051222 | 0.046003 |
| **4** | 0.250752 | 0.247568 | 0.431996 | 0.265543 | 0.012238 | 0.005386 | 0.02833 | 0.020284 |
| **5** | 0.238482 | 0.217898 | 0.388884 | 0.232826 | 0.02266 | 0.003954 | 0.058268 | 0.016982 |
| **6** | 0.2245 | 0.163676 | 0.329916 | 0.175005 | 0.001983 | 0.006399 | 0.006011 | 0.036563 |
| **8** | 0.135963 | 0.074175 | 0.098939 | 0.097045 | 0.000896 | 0.000169 | 0.009061 | 0.001737 |
| **10** | 0.13604 | 0.073641 | 0.045175 | 0.063848 | 0.000606 | 0.001599 | 0.013414 | 0.025042 |
| **11** | 0.13956 | 0.073961 | 0.071576 | 0.06937 | 0.00204 | 0.004981 | 0.028499 | 0.071797 |
| **12** | 0.138416 | 0.072489 | 0.089111 | 0.052519 | 0.000625 | 0.000932 | 0.007013 | 0.017741 |
| **14** | 0.143813 | 0.073623 | 0.091561 | 0.084273 | 0.001428 | 0.000378 | 0.015593 | 0.00448 |

**Subject #3**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 0.440736 | 0.367606 | 1.653006 | 1.456194 | 0.006084 | 0.015144 | 0.003681 | 0.0104 |
| **4** | 0.381974 | 0.267519 | 1.129767 | 0.811863 | 0.002943 | 0.008087 | 0.002605 | 0.009961 |
| **5** | 0.235312 | 0.231279 | 0.709239 | 0.540796 | 0.00156 | 0.007603 | 0.002199 | 0.014058 |
| **6** | 0.234432 | 0.151292 | 0.524214 | 0.40521 | 0.001806 | 0.006842 | 0.003445 | 0.016884 |
| **8** | 0.120498 | 0.062074 | 0.25528 | 0.202199 | 0.000366 | 0.000336 | 0.001435 | 0.001662 |
| **10** | 0.132543 | 0.066952 | 0.091895 | 0.034775 | 0.000268 | 0.00023 | 0.002919 | 0.006628 |
| **11** | 0.122151 | 0.060942 | 0.024337 | 0.022303 | 0.000271 | 0.000326 | 0.011132 | 0.014634 |
| **12** | 0.135527 | 0.068637 | 0.01801 | 0.033209 | 0.000257 | 0.000123 | 0.014251 | 0.00369 |
| **14** | 0.135508 | 0.068566 | 0.012512 | 0.01277 | 0.00057 | 0.000221 | 0.04557 | 0.017284 |

**Subject #4**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 0.614613 | 0.383667 | 0.433863 | 0.223458 | 1.37E-02 | 4.09E-02 | 3.16E-02 | 1.83E-01 |
| **4** | 0.61997 | 0.404072 | 0.449467 | 0.282846 | 1.50E-02 | 5.33E-03 | 3.33E-02 | 1.89E-02 |
| **5** | 0.579296 | 0.259222 | 0.457026 | 0.271117 | 1.96E-02 | 1.72E-03 | 4.29E-02 | 6.34E-03 |
| **6** | 0.346124 | 0.168627 | 0.292326 | 0.162828 | 1.34E-02 | 1.49E-02 | 4.60E-02 | 9.14E-02 |
| **8** | 0.141894 | 0.076707 | 0.173997 | 0.125871 | 4.06E-03 | 2.89E-03 | 2.33E-02 | 2.29E-02 |
| **10** | 0.139539 | 0.071555 | 0.131807 | 0.082746 | 7.20E-03 | 3.79E-03 | 5.46E-02 | 4.58E-02 |
| **11** | 0.161429 | 0.078874 | 0.095875 | 0.046435 | 1.51E-02 | 9.28E-03 | 1.58E-01 | 2.00E-01 |
| **12** | 0.153802 | 0.071618 | 0.043148 | 0.026012 | 6.21E-03 | 3.89E-03 | 1.44E-01 | 1.49E-01 |
| **14** | 0.151115 | 0.076028 | 0.029913 | 0.011953 | 1.93E-03 | 1.86E-03 | 6.45E-02 | 1.55E-01 |

**Subject #5**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 0.781942 | 0.691471 | 1.001104 | 0.417655 | 0.011624 | 0.037985 | 0.011611 | 0.090947 |
| **4** | 0.420836 | 0.562271 | 0.951684 | 0.578646 | 0.00708 | 0.00374 | 0.00744 | 0.006463 |
| **5** | 0.645252 | 0.505247 | 0.748415 | 0.506557 | 0.009178 | 0.002063 | 0.012263 | 0.004072 |
| **6** | 0.296742 | 0.173466 | 0.567172 | 0.392225 | 0.013932 | 0.005991 | 0.024563 | 0.015274 |
| **8** | 0.130296 | 0.080156 | 0.205612 | 0.181703 | 0.000619 | 0.000782 | 0.003012 | 0.004302 |
| **10** | 0.149638 | 0.078864 | 0.106364 | 0.124384 | 0.000585 | 0.000483 | 0.005498 | 0.003883 |
| **11** | 0.151077 | 0.075755 | 0.07344 | 0.098357 | 0.000364 | 0.000704 | 0.00495 | 0.00716 |
| **12** | 0.140447 | 0.077108 | 0.043695 | 0.056834 | 0.000728 | 0.000129 | 0.016654 | 0.002266 |
| **14** | 0.148073 | 0.081313 | 0.037775 | 0.038455 | 0.000311 | 0.000544 | 0.008224 | 0.014147 |

**Subject #6**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 0.674826 | 0.553811 | 0.536734 | 0.179209 | 1.55E-03 | 1.11E-03 | 2.89E-03 | 6.17E-03 |
| **4** | 0.459346 | 0.436774 | 0.54797 | 0.293364 | 2.32E-04 | 5.12E-04 | 4.23E-04 | 1.75E-03 |
| **5** | 0.310858 | 0.21978 | 0.228991 | 0.238236 | 6.06E-04 | 9.71E-05 | 2.65E-03 | 4.07E-04 |
| **6** | 0.138129 | 0.076678 | 0.266446 | 0.229391 | 2.59E-04 | 2.47E-04 | 9.72E-04 | 1.08E-03 |
| **8** | 0.139055 | 0.07312 | 0.092553 | 0.13339 | 1.05E-04 | 5.24E-05 | 1.14E-03 | 3.93E-04 |
| **10** | 0.147827 | 0.073483 | 0.039696 | 0.039318 | 4.40E-05 | 7.46E-05 | 1.11E-03 | 1.90E-03 |
| **11** | 0.140291 | 0.071842 | 0.040711 | 0.026098 | 1.17E-04 | 9.37E-05 | 2.88E-03 | 3.59E-03 |
| **12** | 0.14896 | 0.076691 | 0.056109 | 0.022601 | 9.61E-05 | 3.66E-05 | 1.71E-03 | 1.62E-03 |
| **14** | 0.148674 | 0.07729 | 0.020526 | 0.021234 | 1.47E-04 | 2.47E-05 | 7.15E-03 | 1.16E-03 |

**Subject #7**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 0.557985 | 0.503304 | 1.08737 | 0.934035 | 0.011932 | 0.017349 | 0.010973 | 0.018575 |
| **4** | 0.322195 | 0.326134 | 0.550991 | 0.423895 | 0.003801 | 0.003229 | 0.006898 | 0.007618 |
| **5** | 0.265111 | 0.209986 | 0.405494 | 0.36296 | 0.003554 | 0.005956 | 0.008764 | 0.01641 |
| **6** | 0.134472 | 0.11083 | 0.229747 | 0.181036 | 0.004418 | 0.007453 | 0.019231 | 0.041171 |
| **8** | 0.127178 | 0.09427 | 0.130915 | 0.107978 | 0.001933 | 0.002868 | 0.014764 | 0.026558 |
| **10** | 0.138467 | 0.064979 | 0.041547 | 0.039647 | 0.000478 | 0.0017 | 0.011514 | 0.042875 |
| **11** | 0.137504 | 0.080468 | 0.013797 | 0.004812 | 0.000626 | 0.001598 | 0.045346 | 0.332168 |
| **12** | 0.145271 | 0.078154 | 0.027238 | 0.012696 | 0.000312 | 0.000271 | 0.011461 | 0.021333 |
| **14** | 0.146266 | 0.073092 | 0.051173 | 0.038119 | 0.000244 | 0.000221 | 0.004759 | 0.005801 |

**Subject #8**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 0.642139 | 0.468455 | 0.724147 | 0.300658 | 0.001635 | 0.003211 | 0.002257 | 0.010681 |
| **4** | 0.340762 | 0.227733 | 0.643249 | 0.310745 | 0.001518 | 0.001029 | 0.00236 | 0.00331 |
| **5** | 0.308138 | 0.227235 | 0.310805 | 0.172024 | 0.004651 | 0.001141 | 0.014964 | 0.006632 |
| **6** | 0.16017 | 0.094282 | 0.271773 | 0.314132 | 0.002016 | 0.001814 | 0.007416 | 0.005774 |
| **8** | 0.158004 | 0.07631 | 0.099486 | 0.093109 | 0.000767 | 0.000505 | 0.007713 | 0.005429 |
| **10** | 0.148233 | 0.067838 | 0.028988 | 0.042293 | 0.000366 | 0.00022 | 0.012615 | 0.0052 |
| **11** | 0.147644 | 0.075246 | 0.035557 | 0.04201 | 0.00074 | 0.00011 | 0.020814 | 0.002609 |
| **12** | 0.14907 | 0.078096 | 0.083518 | 0.083031 | 0.000537 | 0.000187 | 0.006433 | 0.002247 |
| **14** | 0.151257 | 0.07214 | 0.065324 | 0.078609 | 0.000504 | 9.38E-05 | 0.00772 | 0.001194 |

**Subject #9**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 0.727791 | 0.464682 | 0.442041 | 0.40795 | 0.003331 | 0.002751 | 0.007535 | 0.006745 |
| **4** | 0.50143 | 0.464006 | 0.379484 | 0.326226 | 0.002106 | 0.00161 | 0.00555 | 0.004935 |
| **5** | 0.476314 | 0.387396 | 0.320784 | 0.163216 | 0.002279 | 0.000894 | 0.007104 | 0.005479 |
| **6** | 0.342411 | 0.301611 | 0.277901 | 0.189953 | 0.002125 | 0.000994 | 0.007645 | 0.005235 |
| **8** | 0.165873 | 0.121661 | 0.238213 | 0.188092 | 0.001422 | 0.000872 | 0.005968 | 0.004635 |
| **10** | 0.156334 | 0.090089 | 0.049292 | 0.06301 | 0.000597 | 0.00032 | 0.012113 | 0.005075 |
| **11** | 0.143503 | 0.064864 | 0.048131 | 0.038511 | 0.000396 | 0.000985 | 0.008225 | 0.025585 |
| **12** | 0.13642 | 0.079961 | 0.016353 | 0.006996 | 0.000331 | 0.000218 | 0.020213 | 0.031175 |
| **14** | 0.154852 | 0.077154 | 0.009381 | 0.008775 | 0.000266 | 0.00012 | 0.028407 | 0.01369 |

**Subject #10**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 0.489366 | 0.398226 | 0.749329 | 0.434461 | 0.003736 | 0.015188 | 0.004986 | 0.034958 |
| **4** | 0.416341 | 0.302666 | 1.009606 | 0.494166 | 0.001941 | 0.002576 | 0.001922 | 0.005214 |
| **5** | 0.408947 | 0.325544 | 0.953664 | 0.550379 | 0.002224 | 0.002563 | 0.002332 | 0.004657 |
| **6** | 0.237411 | 0.154895 | 0.778174 | 0.562572 | 0.001441 | 0.005555 | 0.001851 | 0.009875 |
| **8** | 0.142395 | 0.065584 | 0.230043 | 0.231905 | 0.000506 | 0.00054 | 0.002198 | 0.002328 |
| **10** | 0.140225 | 0.068788 | 0.070011 | 0.058154 | 0.000543 | 0.000204 | 0.007756 | 0.003511 |
| **11** | 0.146888 | 0.073883 | 0.031117 | 0.026703 | 0.000633 | 0.000603 | 0.020343 | 0.022586 |
| **12** | 0.152446 | 0.075078 | 0.123001 | 0.04746 | 0.000508 | 0.000202 | 0.004132 | 0.004255 |
| **14** | 0.155363 | 0.081204 | 0.05013 | 0.089006 | 0.000541 | 0.00022 | 0.010796 | 0.002466 |

**Subject #11**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 1.023588 | 0.317354 | 1.114204 | 0.890683 | 0.008621 | 0.018479 | 0.007738 | 0.020747 |
| **4** | 1.506556 | 0.222904 | 0.963338 | 0.705817 | 0.009756 | 0.008159 | 0.010127 | 0.011559 |
| **5** | 1.456274 | 1.359986 | 1.076009 | 1.254511 | 0.008796 | 0.007817 | 0.008174 | 0.006231 |
| **6** | 1.367042 | 1.429501 | 0.15025 | 0.207673 | 0.005988 | 0.01118 | 0.039855 | 0.053837 |
| **8** | 0.793039 | 0.910842 | 0.254906 | 0.188172 | 0.003925 | 0.004026 | 0.015398 | 0.021393 |
| **10** | 1.046166 | 0.907626 | 0.021974 | 0.035124 | 0.006751 | 0.0034 | 0.307229 | 0.096805 |
| **11** | 1.099557 | 0.967978 | 0.143019 | 0.12834 | 0.007733 | 0.004301 | 0.054067 | 0.033514 |
| **12** | 0.963699 | 0.955054 | 0.12874 | 0.115834 | 0.006445 | 0.004585 | 0.050065 | 0.039582 |
| **14** | 0.685636 | 0.620942 | 0.121391 | 0.094017 | 0.004543 | 0.002528 | 0.037427 | 0.026885 |

**Subject #12**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 0.787125 | 0.473934 | 0.707712 | 0.536495 | 0.00543 | 0.006339 | 0.007673 | 0.011815 |
| **4** | 0.321838 | 0.308349 | 0.441769 | 0.298063 | 0.003307 | 0.003148 | 0.007487 | 0.010563 |
| **5** | 0.251198 | 0.168013 | 0.340379 | 0.254842 | 0.003861 | 0.002665 | 0.011342 | 0.010459 |
| **6** | 0.141337 | 0.109518 | 0.279461 | 0.19651 | 0.003634 | 0.002697 | 0.013004 | 0.013722 |
| **8** | 0.163801 | 0.095404 | 0.188923 | 0.139756 | 0.001998 | 0.002027 | 0.010576 | 0.014501 |
| **10** | 0.1642 | 0.095674 | 0.085709 | 0.133359 | 0.001236 | 0.001807 | 0.014425 | 0.013553 |
| **11** | 0.169669 | 0.093557 | 0.118177 | 0.076438 | 0.00085 | 0.000769 | 0.00719 | 0.010058 |
| **12** | 0.155736 | 0.08616 | 0.045683 | 0.056337 | 0.000608 | 0.000514 | 0.013314 | 0.009127 |
| **14** | 0.155349 | 0.086092 | 0.022904 | 0.020986 | 0.000325 | 0.000203 | 0.014172 | 0.009677 |

**Subject #13**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 0.546663 | 0.512757 | 1.22916 | 0.910007 | 0.011964 | 0.012963 | 0.009733 | 0.014244 |
| **4** | 0.452505 | 0.349537 | 0.861173 | 0.566588 | 0.006038 | 0.004379 | 0.007012 | 0.007729 |
| **5** | 0.369302 | 0.294757 | 0.716988 | 0.520155 | 0.006161 | 0.003352 | 0.008592 | 0.006445 |
| **6** | 0.215822 | 0.149663 | 0.434768 | 0.295776 | 0.005942 | 0.005309 | 0.013667 | 0.017951 |
| **8** | 0.149174 | 0.097234 | 0.231606 | 0.217801 | 0.00421 | 0.002311 | 0.018177 | 0.01061 |
| **10** | 0.143889 | 0.073774 | 0.088974 | 0.067182 | 0.001172 | 0.00209 | 0.013169 | 0.031111 |
| **11** | 0.150524 | 0.073161 | 0.048782 | 0.031052 | 0.001904 | 0.002757 | 0.039021 | 0.088776 |
| **12** | 0.148314 | 0.076039 | 0.102048 | 0.043613 | 0.001504 | 0.00139 | 0.01474 | 0.031866 |
| **14** | 0.149938 | 0.080459 | 0.056556 | 0.068166 | 0.000574 | 0.000876 | 0.010151 | 0.012858 |

**Subject #14**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 0.628221 | 0.595022 | 0.1528 | 0.120514 | 0.072359 | 0.043029 | 0.473553 | 0.357046 |
| **4** | 0.487913 | 0.428446 | 0.16327 | 0.103195 | 0.065964 | 0.036213 | 0.404017 | 0.350917 |
| **5** | 0.407418 | 0.398007 | 0.083812 | 0.070784 | 0.031158 | 0.033031 | 0.37176 | 0.466651 |
| **6** | 0.316071 | 0.227487 | 0.176265 | 0.072855 | 0.015593 | 0.01001 | 0.088461 | 0.137392 |
| **8** | 0.172268 | 0.100875 | 0.058133 | 0.040479 | 0.008851 | 0.007091 | 0.152261 | 0.175167 |
| **10** | 0.159374 | 0.089951 | 0.020385 | 0.014782 | 0.008324 | 0.005882 | 0.408333 | 0.397924 |
| **11** | 0.146442 | 0.088942 | 0.011091 | 0.018673 | 0.006299 | 0.004768 | 0.567901 | 0.255339 |
| **12** | 0.150214 | 0.081316 | 0.024454 | 0.057693 | 0.007046 | 0.003807 | 0.288136 | 0.065984 |
| **14** | 0.136712 | 0.069731 | 0.026614 | 0.008476 | 0.002893 | 0.002213 | 0.108696 | 0.261134 |

**Subject #15**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 0.703992 | 0.641863 | 0.419623 | 0.459288 | 0.030192 | 0.0276 | 0.07195 | 0.060093 |
| **4** | 0.667641 | 0.578226 | 0.385791 | 0.300866 | 0.015194 | 0.0131 | 0.039384 | 0.043541 |
| **5** | 0.431293 | 0.396041 | 0.244799 | 0.209175 | 0.016412 | 0.010418 | 0.067043 | 0.049806 |
| **6** | 0.285881 | 0.241674 | 0.167095 | 0.127717 | 0.012288 | 0.011672 | 0.073541 | 0.091392 |
| **8** | 0.151404 | 0.119506 | 0.075375 | 0.049374 | 0.011062 | 0.006791 | 0.146765 | 0.137546 |
| **10** | 0.150856 | 0.077044 | 0.051645 | 0.035881 | 0.00472 | 0.002855 | 0.091384 | 0.079562 |
| **11** | 0.148855 | 0.078612 | 0.037996 | 0.017278 | 0.002396 | 0.000793 | 0.063047 | 0.045908 |
| **12** | 0.14887 | 0.078202 | 0.015162 | 0.00628 | 0.003332 | 0.002059 | 0.219731 | 0.327824 |
| **14** | 0.142387 | 0.072193 | 0.035865 | 0.03422 | 0.002082 | 0.001791 | 0.058052 | 0.052343 |

**Subject #16**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 0.681297 | 0.379683 | 0.731917 | 0.683852 | 0.016853 | 0.020583 | 0.023025 | 0.030099 |
| **4** | 0.509081 | 0.406458 | 0.199723 | 0.272692 | 0.008451 | 0.00761 | 0.042311 | 0.027907 |
| **5** | 0.439067 | 0.291231 | 0.135629 | 0.099325 | 0.013472 | 0.009556 | 0.099333 | 0.096205 |
| **6** | 0.188885 | 0.119954 | 0.089519 | 0.090231 | 0.008421 | 0.016439 | 0.094067 | 0.182186 |
| **8** | 0.140503 | 0.069487 | 0.073577 | 0.070309 | 0.001474 | 0.002331 | 0.020036 | 0.03315 |
| **10** | 0.144166 | 0.073436 | 0.080133 | 0.059038 | 0.001228 | 0.001144 | 0.015327 | 0.019373 |
| **11** | 0.161301 | 0.075827 | 0.058726 | 0.051355 | 0.00061 | 0.00034 | 0.010387 | 0.006614 |
| **12** | 0.152023 | 0.081713 | 0.063692 | 0.043208 | 0.000473 | 0.000923 | 0.007419 | 0.021369 |
| **14** | 0.152104 | 0.074455 | 0.062345 | 0.044727 | 0.000436 | 0.000287 | 0.006997 | 0.006427 |

**Subject #17**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 0.59159 | 0.503524 | 0.819079 | 0.626834 | 0.016564 | 0.017378 | 0.020222 | 0.027723 |
| **4** | 0.414455 | 0.348487 | 0.80298 | 0.555148 | 0.003108 | 0.00306 | 0.003871 | 0.005512 |
| **5** | 0.287438 | 0.224795 | 0.603532 | 0.490974 | 0.015039 | 0.001004 | 0.024918 | 0.002044 |
| **6** | 0.217716 | 0.210447 | 0.588706 | 0.418892 | 0.007559 | 0.002432 | 0.01284 | 0.005806 |
| **8** | 0.145381 | 0.077345 | 0.185171 | 0.19454 | 0.003207 | 0.001827 | 0.017318 | 0.009389 |
| **10** | 0.137388 | 0.074508 | 0.08116 | 0.071592 | 0.003167 | 0.001209 | 0.039021 | 0.016894 |
| **11** | 0.137431 | 0.070151 | 0.091311 | 0.105927 | 0.003586 | 0.001872 | 0.039273 | 0.017675 |
| **12** | 0.141112 | 0.068744 | 0.053278 | 0.07575 | 0.001763 | 0.000984 | 0.033093 | 0.012993 |
| **14** | 0.138822 | 0.069811 | 0.053319 | 0.088657 | 0.000833 | 0.000161 | 0.015616 | 0.001813 |

**Subject #18**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 0.540103 | 0.510207 | 0.758724 | 0.508751 | 0.019225 | 0.019088 | 0.025339 | 0.03752 |
| **4** | 0.420428 | 0.376626 | 0.630746 | 0.569249 | 0.003005 | 0.003484 | 0.004764 | 0.00612 |
| **5** | 0.309992 | 0.298298 | 0.614148 | 0.473242 | 0.010678 | 0.000527 | 0.017386 | 0.001114 |
| **6** | 0.257083 | 0.215172 | 0.536203 | 0.394918 | 0.009424 | 0.002094 | 0.017575 | 0.005304 |
| **8** | 0.150864 | 0.144955 | 0.314565 | 0.185352 | 0.002831 | 0.013602 | 0.009001 | 0.073386 |
| **10** | 0.148207 | 0.080451 | 0.278449 | 0.168726 | 0.003666 | 0.001321 | 0.013164 | 0.00783 |
| **11** | 0.142706 | 0.07385 | 0.233454 | 0.102322 | 0.003275 | 0.001724 | 0.01403 | 0.016849 |
| **12** | 0.137271 | 0.072586 | 0.079298 | 0.074632 | 0.001227 | 0.000756 | 0.015475 | 0.010134 |
| **14** | 0.13193 | 0.070087 | 0.089214 | 0.086903 | 0.000691 | 0.000168 | 0.007741 | 0.001937 |

**Subject #19**

| | TF1 | | TF2 | | TF3 | | TF4 | |
|---|---|---|---|---|---|---|---|---|
| **Hz** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** | **1RMS** | **2RMS** |
| **3** | 0.390879 | 0.444026 | 1.142866 | 0.959345 | 0.021107 | 0.01418 | 0.018468 | 0.014781 |
| **4** | 0.492416 | 0.371468 | 0.57118 | 0.430671 | 0.009751 | 0.006712 | 0.017072 | 0.015585 |
| **5** | 0.38588 | 0.331357 | 0.416316 | 0.367397 | 0.00332 | 0.003416 | 0.007974 | 0.009299 |
| **6** | 0.245556 | 0.197996 | 0.240113 | 0.184999 | 0.004848 | 0.004187 | 0.020192 | 0.02263 |
| **8** | 0.133269 | 0.09172 | 0.134896 | 0.109206 | 0.006373 | 0.003118 | 0.047244 | 0.028554 |
| **10** | 0.140327 | 0.074241 | 0.042456 | 0.039914 | 0.003884 | 0.002349 | 0.091483 | 0.058848 |
| **11** | 0.156521 | 0.079069 | 0.014146 | 0.004832 | 0.003005 | 0.002011 | 0.212411 | 0.416084 |
| **12** | 0.153071 | 0.076673 | 0.027998 | 0.012782 | 0.001669 | 0.001687 | 0.059611 | 0.13268 |
| **14** | 0.150481 | 0.083107 | 0.052612 | 0.03844 | 0.000962 | 0.001184 | 0.018289 | 0.03079 |

## 5.2 Subject data with skin motion artifact

**KEY ⟶ CF-Correction Factor**

**Subject #18**

| Hz | CF | 1RMS Lumbar rotation(deg) | 2RMS Lumbar rotation(deg) | CF * 1RMS Lumbar rotation(deg) | CF * 2RMS Lumbar rotation(deg) |
|---|---|---|---|---|---|
| **3** | 0.995 | 4.6327 | 7.512 | 4.6095365 | 7.47444 |
| **4** | 0.9912 | 2.6984 | 4.6439 | 2.67465408 | 4.60303368 |
| **5** | 0.9863 | 2.197 | 3.7497 | 2.1669011 | 3.69832911 |
| **6** | 0.9803 | 1.8263 | 2.4768 | 1.79032189 | 2.42800704 |
| **8** | 0.9755 | 1.6293 | 1.9763 | 1.58938215 | 1.92788065 |
| **10** | 0.9689 | 0.8591 | 0.5446 | 0.83238199 | 0.52766294 |
| **11** | 0.9564 | 0.6495 | 0.3872 | 0.6211818 | 0.37031808 |
| **12** | 0.945 | 0.3479 | 0.3249 | 0.3287655 | 0.3070305 |
| **14** | 0.9312 | 0.1873 | 0.2817 | 0.17441376 | 0.26231904 |

**Subject #19**

| Hz | CF | 1RMS Lumbar rotation(deg) | 2RMS Lumbar rotation(deg) | CF*1RMS Lumbar rotation(deg) | CF*2RMS Lumbar rotation(deg) |
|---|---|---|---|---|---|
| **3** | 0.9887 | 3.2214 | 7.0171 | 3.18499818 | 6.93780677 |
| **4** | 0.9798 | 2.8258 | 5.6129 | 2.76871884 | 5.49951942 |
| **5** | 0.9682 | 2.6406 | 3.2437 | 2.55662892 | 3.14055034 |
| **6** | 0.9639 | 2.7908 | 3.512 | 2.69005212 | 3.3852168 |
| **8** | 0.9595 | 1.2114 | 1.816 | 1.1623383 | 1.742452 |
| **10** | 0.9486 | 0.3063 | 0.46 | 0.29055618 | 0.436356 |
| **11** | 0.9432 | 0.1825 | 0.4468 | 0.172134 | 0.42142176 |
| **12** | 0.9387 | 0.2264 | 0.4572 | 0.21252168 | 0.42917364 |
| **14** | 0.9324 | 0.3368 | 0.5902 | 0.31403232 | 0.55030248 |