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# Characterization of Postural Stability in a Simulated Environment of an Earthquake Using In-Shoe Plantar Pressure Measurement

**Ziad O. Abu-Faraj, Ph.D.,** ***Senior Member*****, IEEE; Fadi A. Abou-Assi,** ***Student Member*****, IEEE; Rawad K. Jaber,** ***Student Member*****, IEEE; Hassan A. Khalifeh,** ***Student Member*****, IEEE**

Department of Biomedical Engineering, American University of Science and Technology, Beirut, Lebanon

*Abstract*—**An abled individual is believed to be capable of withstanding and overcoming the severe tremors of an earthquake as has been ascertained in a previous study. However, the event-related physiological mechanisms of human postural stability during an earthquake are subject to further investigation. Accordingly, the objective of this study is to further characterize postural stability in a simulated environment of an earthquake using a pedar-x (novel gmbh, Munich, Germany) in-shoe dynamic plantar pressure measurement system. A foot mask, dividing each of the insoles into seven plantar loading regions, was employed in this study. This paper reports preliminary results obtained from a normal adult female test subject with right side dominance and a normal foot arch. The test trial was comprised of 12 stages, ranging from quiet standing to simulated earthquake magnitude of 6.7 degrees on the Richter's scale, which is considered to be violent. The study metrics included: mean plantar pressure, foot-to-ground contact duration, insole loading area, and the position, displacement, and instantaneous velocity of the center of pressure. The study showed bilateral quantifiable changes in these metrics by foot-mask-region as a result of increasing magnitudes of simulated tremors. The subject was able to defy the overwhelming perturbations and maintain her balance and postural stability throughout the test period. The significance of this study lies in its ability to determine the threshold of falling within different subject populations in the event of an earthquake.**

*Keywords*—Postural Stability; Postural Control; Balance; Plantar Pressure; Center of Pressure; Earthquake Simulator; Pedar-x.

## I. Introduction

POSTURAL CONTROL in bipeds is an essential neuromusculoskeletal functional task that prevents them from an inevitable collapse. Postural control is relentlessly challenged by a barrage of physiological and daily environmental changes that, if uncontrolled, could result in the threatening of postural stability. Instances of such changes include: diseases, gravity, terrains, airplanes, elevators, escalators, trains, buses, and seismic activities.

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Z. O. Abu-Faraj is the Founding Chair of the Department of Biomedical Engineering at the American University of Science and Technology, Beirut, Lebanon (telephone: +961-1-218716 ext. 249; facsimile: +961-1-339302; e-mail: bme@aust.edu.lb), while the co-authors are senior-year biomedical engineering students at the same institution.

In the event of an earthquake, the interaction between the central and peripheral nervous systems and the musculoskeletal system is significantly perturbed, and its complexity is unquestionably blown out of proportion. However, an abled individual is capable of withstanding and overcoming the severe tremors of an earthquake. Understanding the event-related physiological mechanisms of human postural stability could be useful in determining the threshold of falling within different subject populations during an earthquake.

An original study of postural stability and balance in the unstable environment of an earthquake, reported by our group in 2008, ascertained that an abled human being could be trained to cognitively adapt and retain over long stretches of time the neuromusculoskeletal responses to the impact of increased simulated earthquake tremors [1]. The study investigated the lower-extremity muscular response and head acceleration in ten-abled adult subjects for maintaining postural stability during the event of a simulated seismic activity. The study concluded by suggesting that an earthquake simulator be used in schools, rehabilitation centers, and other community public service locations, found on seismic belts, to train individuals who are at risk of falling against possible earthquakes.

The objective of the current study is to further characterize postural stability in a simulated environment of an earthquake using in-shoe dynamic plantar pressure measurement. This paper reports preliminary results obtained from an adult female test subject.

The measurement of dynamic pressures beneath the plantar aspect of the foot provides a quantitative means of assessing the plantar weight bearing patterns reflective of the biomechanical transfer of load through the structure of the foot. Moreover, such measurements allow one to identify the locus and instantaneous velocity of the center of pressure (COP), among other metrics, beneath the feet, and thus the ability to discern their correlation to postural stability. Furthermore, plantar pressure measurements have been used to identify areas of repetitive stress on the plantar surface of the normal and pathological foot in an objective manner, as well as in studying the progression of various foot disorders. Our previous studies on plantar pressures range form systems development [2-4] to clinical applications [5-7].

## II. Literature Review

### A. Postural Stability Studies

Although studies on postural stability and balance have been extensive, literature, to the knowledge of the authors, had not addressed the study of postural stability and balance in the unstable environment of an earthquake prior to 2008 [1].

Henry *et al*. have investigated control of stance during surface translations [8], while Almeida *et al.* have studied the postural strategy to maintain balance on the seesaw [9], and Robinson *et al.* have designed a sliding linear investigative platform for analyzing lower limb stability [10]; the same platform was used by Richerson *et al*. to detect the acceleration threshold during short anterior and posterior translational perturbations on the platform [11].

### B. Plantar Pressure Studies

Studies on plantar pressures have substantially increased in recent years. Stewart *et al*. performed a comparative study of the difference in in-shoe plantar pressure distribution between the Massai Barefoot Technology® shoes and flat-bottomed training shoes [12]. Scott *et al*. studied the age-related differences in foot structure and function in young and older people [13]. Bosh *et al*. provided preliminary normative values for foot loading patterns and foot shape parameters of the developing child [14]. Wang and Watanabe investigated the effect of obstacle height on the velocity of the COP during obstacle crossing [15]. De Cock *et al*. reported on the use of the trajectory of the COP as a potential measure for foot function during barefoot running [16]. Chuckpaiwong *et al*. investigated the effect of foot type on in-shoe plantar pressure during walking and running [17]. Crosbie *et al*. studied the pressure characteristics in the painful *pes cavus* resulting from Charcot-Marie-Tooth disease [18]. Turner and Woodburn studied the clinical and biomechanical characteristics of severely deformed feet in patients with rheumatoid arthritis [19]. Bisiaux and Moretto assessed the effects of fatigue on plantar pressure distribution in walking [20].

## III. Materials and Methods

The earthquake simulator utilized herein was extensively described and validated in a previous study [1]. It was designed to replicate the Love wave since it is considered to be the most accountable for causing damage among the four types of earthquake activities. The simulated earthquake magnitudes were selected between 4.5 and 6.5 degrees on the Richter's scale. These values correspond to tremor effects of Mediocre and Violent, respectively, while the intermediate values are distributed as follows in ascending order: 4.8 = Strongly; 5.4 = Much Fort; and 6.1 = Strong. Magnitudes in excess of 6.7, also considered violent, were excluded from the design because of safety considerations towards the test subjects.

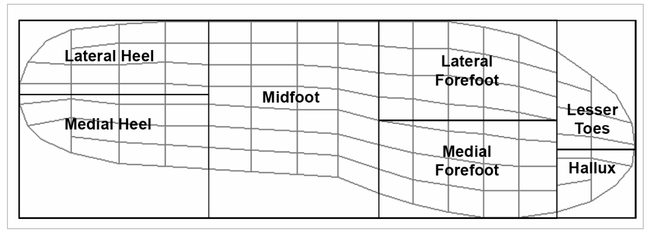


**Figure 1. The foot mask used to define the seven plantar loading regions.**

A pedar-x (novel gmbh, Munich, Germany) in-shoe pedobarograph system was used to collect the dynamic plantar pressure history for this study. The system is driven by a pedar-x Recorder v. 12.1.30e software platform and database essential v. 14.3.12e installed on a Toshiba Satellite™ A200-24A (Toshiba Corp., Minato-ku, Tokyo, Japan) notebook with a 1.73 GHz Pentium® (Intel Corp., Santa Clara, CA, USA) dual processor and 0.99 GB of RAM. A Logitech® (Fremont, CA, USA) digital webcam was used to capture the motion pictures of the test subject in the sagittal plane; and was synchronized with the plantar pressure data via the data acquisition software.

Each of the system's 2.5 mm-thick insoles consists of 99 capacitive sensors with an average sensor area of 126 $mm^2$. The insole sensors were calibrated using a trublu® (novel gmbh, Munich, Germany) bladder-based calibration device. The raw plantar pressure data is sampled at 100 Hz per sensor and automatically transferred from the portable unit to the notebook via a Bluetooth® telemetry system for later processing. The insoles were fitted into a pair of standard canvas trainers (Converse®, Chuck Taylor All Star, North Andover, MA, USA). These laboratory-control shoes were selected in order to minimize support provided by the shoe structure, yet offering a suitable platform for the instrumented insole. The existing structure of the shoes was not altered.

A foot mask, dividing each of the insoles into seven plantar loading regions, was used in this study as follows: Medial Heel (MH), Lateral Heel (LH), Midfoot (MF), Medial Forefoot (MFF), Lateral Forefoot (LFF), Hallux (HX), and Lesser Toes (LT). This foot mask is illustrated in Figure 1.

A female adult volunteer (Age: 18.75 years; Height: 162 cm; Mass: 52 kg), free from any musculoskeletal or neurological disorders, and who is right-side-dominant with a normal foot arch, participated in this study. The participant signed an *informed consent form for research subjects* prior to testing. Because of the ability to cognitively learn and retain the impact of earthquake tremors [1], the subject was selected such that she had no prior experience with the earthquake simulator, and the study was limited to a single test trial. This test trial was comprised of 12 stages of 10 seconds each; starting with quiet standing (QS) and followed by increasing simulated earthquake magnitudes from 4.5 to 6.7 degrees on the Richter's scale. The 10-second epochs were


**Figure 2. The instrumented subject on the earthquake simulator during the study trial.**

selected from the onset of the period when the oscillation of the earthquake simulator's platform reached its steady state. During testing, the instrumented subject stood in a comfortable posture on the simulator such that the platform oscillations were orthogonal to her coronal plane (i.e., in the anterior-posterior direction) as illustrated in Figure 2. The subject was not harmed during testing nor exhibited any signs of discomfort or fatigue.

Because of their relevance to postural stability, the metrics that were considered in the data analysis included the following: mean plantar pressure (*kPa*), foot-to-ground contact duration (*% of Total Time*), insole loading area (*% of Total Insole Area*), COP position on the *x*-axis (medial-lateral direction) (*% of Insole Width*), COP position on the *y*-axis (posterior-anterior direction) (*% of Insole Length*), COP excursion with respect to the *x*-axis (medial-lateral direction) (*% of Insole Width*), COP excursion with respect to the *y*-axis (posterior-anterior direction) (*% of Insole Length*), COP instantaneous velocity in the *x*-direction (*mm/s*), and COP instantaneous velocity in the *y*-direction (*mm/s*).

Since the pedar-x *Step Analysis* software is restricted to ambulation, a custom-software was developed in this study to compute the above metrics for postural stability on the earthquake simulator.

## IV. RESULTS

The results obtained from this study by metric value for the entire range of simulated earthquake magnitudes, from quiet standing to 6.7 degrees on the Richter's scale, are presented in Figure 3. Mean plantar pressure values for the seven foot masks revealed noticeable bilateral changes commensurate with increasing earthquake magnitudes, mainly in the loading of the HX and LT regions. The mean foot-to-ground contact duration, by foot mask, did not show any marked changes in the left foot, but some variability were

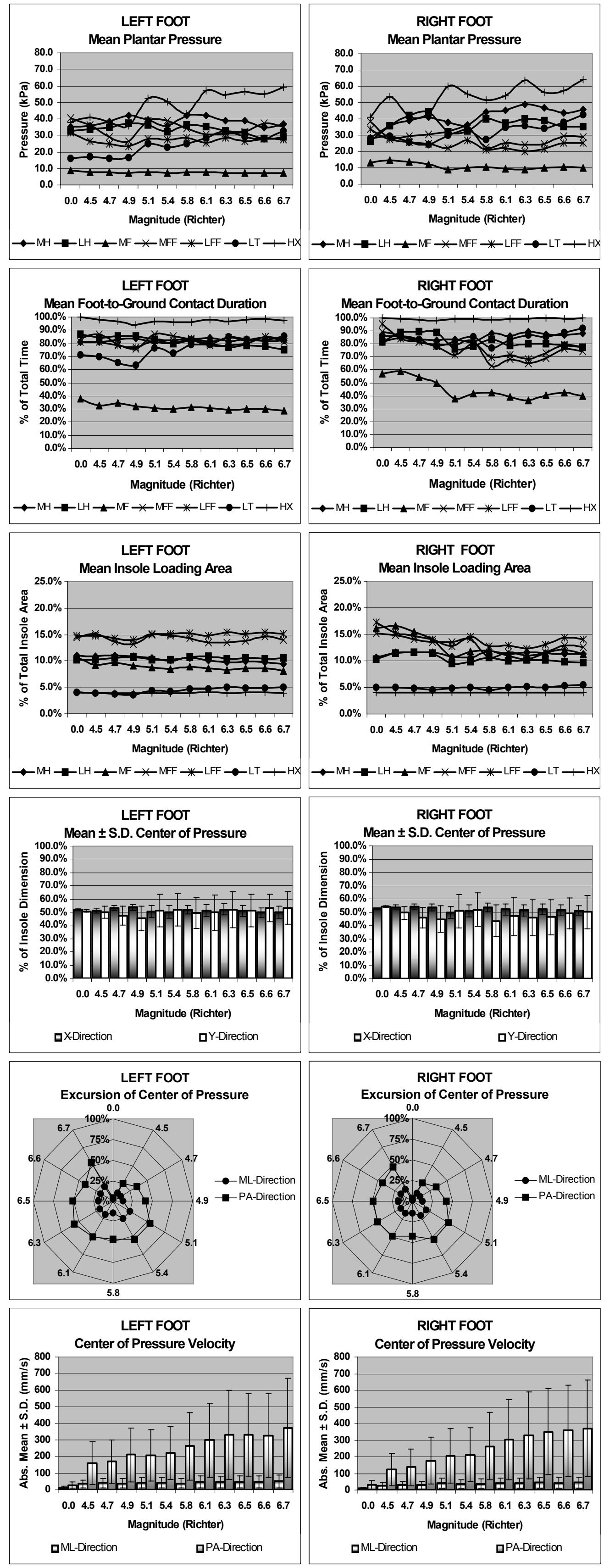


**Figure 3. The bilateral study results by metric value for the entire range of simulated earthquake magnitudes starting with quiet standing.**

observed in the LH, MF, MFF, and LFF of the right foot. Interestingly, the HX maintained almost a 100% bilateral contact with the ground. As expected for a normal arched foot, the MF manifested the least contact among the seven foot masks. The mean insole loading area for all foot masks for the left foot did not change. Some reductions in this metric were observed in the MF, MFF, and LFF regions of the right foot. The COP position in the medial-lateral (ML) and posterior-anterior (PA) directions showed that the bilateral mean values remained central to the insole dimensions; while the standard deviation (S.D.) values increased as the tremor increased. The bilateral excursion of the COP increased gradually in the ML-direction from the center of the insole to 25% of the insole width. The bilateral excursion of the COP in the PA-direction increased from the center of the insole to 50% of the insole length. Both of these increases were symmetrical with respect to the geometric center of the insole. The bilateral instantaneous velocity of the COP, taken in absolute value to account for the forward and backward oscillations of the earthquake simulator's platform, showed a slight increase in the mean value in the ML-direction, while a marked increase was observed in the PA-direction. The standard deviation of this metric also increased bilaterally with increasing tremors in both directions.

## V. Discussion And Conclusions

This study has characterized the postural stability, of a right-sided dominant abled adult individual with a normal foot arch, in a simulated environment of an earthquake using in-shoe dynamic plantar pressure measurement. The subject was able to defy the overwhelming perturbations and maintain her balance and postural stability throughout the test period. The effect of the dominant foot on postural stability was not clearly evident from the obtained results; and, hence, is a subject of further investigation, which is beyond the scope of this paper. The significance of this study lies in its ability to determine the threshold of falling within different subject populations in the event of an earthquake; a fact which is subject to future research.

Future studies involving the earthquake simulator will: i) expand the current study to encompass a larger sample population; ii) investigate the effect of transient response of the oscillation of the platform on postural stability; iii) investigate the effect of the dominant foot side on postural stability; iv) investigate the changes in the plantar pressure metrics between the onset trial and a one-week follow-up trial; v) determine the threshold of falling within different subject populations; and vi) study the effects of different foot types on postural stability.

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