World Academy of Science, Engineering and Technology
International Journal of Physical and Mathematical Sciences
Vol:9, No:1, 2015

Fiber Braggs Grating Sensor Based Instrumentation to Evaluate Postural Balance and Stability on an Unstable Platform

Chethana K., Guru Prasad A. S., Vikranth H. N., Varun H., Omkar S. N., Asokan S.

***Abstract*—**This paper describes a novel application of Fiber Braggs Grating (FBG) sensors in the assessment of human postural stability and balance on an unstable platform. In this work, FBG sensor Stability Analyzing Device (FBGSAD) is developed for measurement of plantar strain to assess the postural stability of subjects on unstable platforms during different stances in eyes open and eyes closed conditions on a rocker board. The studies are validated by comparing the Centre of Gravity (CG) variations measured on the lumbar vertebra of subjects using a commercial accelerometer. The results obtained from the developed FBGSAD depict qualitative similarities with the data recorded by commercial accelerometer. The advantage of the FBGSAD is that it measures simultaneously plantar strain distribution and postural stability of the subject along with its inherent benefits like non-requirement of energizing voltage to the sensor, electromagnetic immunity and simple design which suits its applicability in biomechanical applications. The developed FBGSAD can serve as a tool/yardstick to mitigate space motion sickness, identify individuals who are susceptible to falls and to qualify subjects for balance and stability, which are important factors in the selection of certain unique professionals such as aircraft pilots, astronauts, cosmonauts etc.

***Keywords*—**Biomechanics, Fiber Bragg Gratings, Plantar Strain Measurement, Postural Stability Analysis.

I. Introduction

STANDING balance is an essential constituent of most weight bearing tasks and engages a wide variety of sensory inputs [1]-[3]. Generally, the balance can be defined as the ability to maintain the body's Centre of Gravity (CG) over its base of support with minimal sway or maximal steadiness [4]. It has been suggested by Woollacott et al. [5] that postural control has substantial attentional requirements, with sway depending on the postural tasks, individual's age, and balancing capabilities. The fall-related injuries pose a massive burden on geriatric population [6], sports performance [7], and patients suffering from diabetes mellitus [8]. Several studies undertaken on postural stability and balance [9] have focused on the postural disposition and its possible consequences on instability [10]; ground reaction force (GRF) for balance assessment [11]; challenges in medio-lateral postural stability during a swift upward step [12]; effects of vibration sensation, vision and vestibular asymmetry in postural control of healthy elderly subjects [13]; human postural responses to different frequency vibrations of lower extremity muscles [14]; evaluation of visual effects on postural control and balance [15]; usage of control models in the analysis of human postural balance [16], [17]; feature selection of stabilometric parameters in quantitative posturography [18]; application of non-equilibrium statistical mechanics in posture control [19]; utilization of control systems to model the preceding motor command applied by able-bodied subjects during quiet standing [20]; study of implicit motor learning of a balancing task [21]; investigation of the interference between postural control and cognitive processing in patients with surgically confirmed unilateral vestibular lesions [22]; study of functional status of children after treatment for a malignant tumour of the Central Nervous System (CNS) [23]; study of the effects of aging and sensory reintegration on attentional demands for postural control [24]; determination of the effects of dual tasks performance on postural instability in subjects with idiopathic Parkinson's disease [25]; study of standing balance recovery from stroke [26]; the investigation of the relationship between chronic ankle instability and postural instability [27].

Many investigations have been reported in the literature [28]-[30], in the area of postural stability analysis that utilise inertial sensing, optical motion capture system, force plates, etc. For example, Winter et al. [31] have explored the possibility of evaluating details pertinent to human balance and stability in various contexts such as bipedal and uni-pedal stance, with and without visual feedback. There are many unstable platforms such as rocker boards, wobble boards, stability pads, etc. used to improve the balance [32], coordination skills, and weight distribution, to avoid falls, and to prevent sports-related injuries [33]-[35]. Omkar et al. [35] have studied the angular deviations of the human body at the CG while standing on a rocker board. It has been shown that the measurement of dynamic strains beneath the plantar aspect

Chethan K. is a Ph.D. student in Department of Instrumentation and Applied Physics, Indian Institute of Science, Bangalore, India, working in the area of FBG sensors for biomechanical applications (e-mail: chethana4prasad@ gmail.co.in).

Guru Prasad A. S. is with Nanyang Technological University, Singapore working on Optical Metrology for Rolls-Royce Pte Ltd, Singapore (guruprasadasblr@gmail.com).

Vikranth H. N. obtained his M. Des. Degree at the Center for Product Design and Manufacturing, Indian Institute of Science, Bangalore, India (e-mail: vikrantmvit@gmail.com).

Varun H worked as a project intern in Department of Aerospace Engineering, Indian institute of Science, Bangalore, India.

Omkar S. N. is a Principle Research Scientist in the Department of Aerospace Engineering, Indian Institute of Science, Bangalore, India (e-mail: Omkar@aero.iisc.ernet.in).

Asokan S. is a professor in Department of Instrumentation and Applied Physics and Robert Bosch Centre for Cyber Physical Systems, Indian Institute of Science, Bangalore, India (e-mail: sundarrajan.asokan@gmail.com).

of the foot provides a quantitative means of assessing the plantar weight bearing patterns indicative of the biomechanical transfer of load through the structure of the foot.

Earlier, the feasibility of FBG sensor based instrumentation for plantar strain measurements on a static platform has been demonstrated by Guru Prasad et al. [36]. However, the use of FBG sensors in the study of postural stability and balance in an unstable environment like a rocker board has been minimally reported in literature. The present study is an extension of the work carried out by Guru Prasad et al. [36], towards understanding the postural balance and stability of subjects under unstable/dynamic conditions as it simulates many real-life conditions.

In the present work, a FBG Stability Analyzing Device (FBGSAD) has been developed, and tested for assessing the postural balance and stability from the recorded strain data of FBG sensors. The developed FBGSAD uses 6 strain sensors at various locations of the plantar aspect to assess the postural stability of subjects on unstable platforms during different stances such as bipedal and uni-pedal stance, Eyes Open and Eyes Closed conditions on a rocker board. The results are validated by comparing the CG variations measured simultaneously at the second lumbar vertebra of subjects using a commercial accelerometer [37]-[47].

In the following section (section II), the details of the experiments carried out and protocols adopted for quantification of plantar strains on an unstable platform are outlined. Section III provides a brief description of the instrumentation, namely FBG sensors and accelerometers. The postural stability analysis for various participants is provided in Section IV.

II. Methods and Materials

A. Subjects

10 healthy subjects (5 female and 5 male; mean ± SD age = 26 ± 3 years), free from any neuro-musculo-skeletal illnesses, participated in this study. Subjects with similar foot sizes have been chosen to suit the developed FBGSAD. These subjects have been advised not to consume alcohol or any sort of medication 24 hours prior to the onset of the experiment.

B. Layout

An outline of the FBGSAD comprising of FBG sensors bonded between two Perspex sheets is shown in Fig. 1 which is similar to that proposed by Guru Prasad et al. [36] for static conditions. Individual strain sensing plates for both the feet are firmly secured on a wooden plank. The upper Perspex sheet of the sensing plate is divided into three separate segments, each comprising of one FBG sensor. For the current feasibility study, three sensors for each foot at biomechanically significant positions, namely the fore-foot, mid-foot and hind-foot are chosen to measure the plantar strains [48]. Independent fibers (channel 1 and channel 2), each carrying three FBGs of varying Bragg wavelengths have been used for each of the foot. A small protrusion is provided at the end of the Perspex sheet serving as a reference or datum for the subjects to appropriately position their feet on the plantar sensing plate. This plantar sensing plate with FBG sensors on the wooden plank is then secured firmly on top of a rocker board as shown in Figs. 2 and 3 to form FBGSAD, and to evaluate the postural stability of subjects under dynamic/unstable conditions.

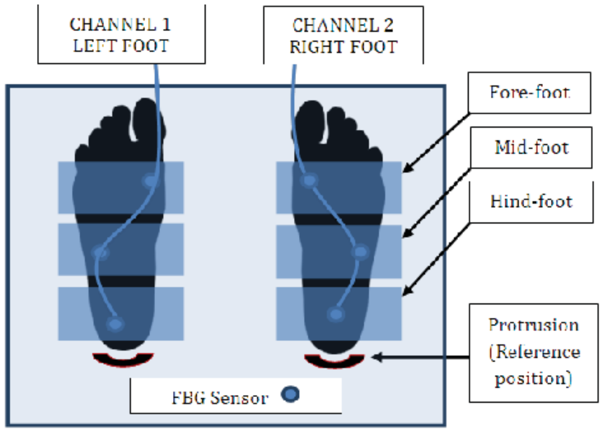

Fig. 1 Schematic design of the plantar strain sensing plate

Fig. 2 The Rocker board

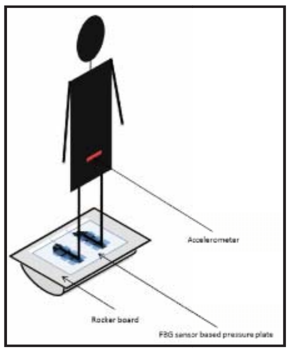

Fig. 3 Schematic of the subject standing on a rocker board

C. Procedure

The experiment is conducted in an isolated room in order to eliminate any possibility of external vibrations interfering with the recorded plantar strain data. Subjects are instructed to comfortably ingress on the FBGSAD with the heels touching the small protrusions provided at the end of each foot on the sensing plate. An accelerometer is mounted on the subject's CG i.e., second lumbar vertebra [49].

Table I details the different cases of the tasks performed in the present study. Volunteers are instructed to stand on the plantar strain sensing rocker board without any footwear for the following cases i.e., Bipedal eyes Open (BO), Bipedal eyes Closed (BC), Unipedal eyes Open (UO) and Unipedal eyes Closed (UC) for 2 minutes with an interim gap of 5 minutes between each case to avoid any possible error due to muscle fatigue.

TABLE I
DIFFERENT CASES CONSIDERED

Case	Stance	Visual Input
BO	Bipedal	Yes
BC	Bipedal	No
UO	Unipedal	Yes
UC	Unipedal	No

Subjects are asked to maintain a uni-pedal stance on the rocker board on one of their legs as steadily as possible. Further, they are asked to fixate their gaze on a black cross, placed on the wall at eye level, about 2.5 meters away from the subject. The arms are made to hang by their sides and support from the elevated leg is not permitted to ensure proper stance. Subjects have been given detailed instructions prior to data acquisition and each subject is given a trial run session for each of the cases mentioned in Table I (BO, BC, UO and UC).

Three trials of readings are recorded for each case. The protocol is such that readings are first taken for bi-pedal conditions followed by uni-pedal conditions.

III. SENSOR INSTRUMENTATION DETAILS

A FBG is a periodic or quasi-periodic modulation of the refractive index of the core of the photosensitive, germania doped silica fiber achieved by exposing it to intensity modulated UV light [50]. Over the years, there have been several techniques developed to inscribe the gratings in an optical fiber [51], [52]. The phase mask method is used in the present study with the UV radiation from a 248nm KrF laser [53].

In order to facilitate easy post-processing of the data, FBGSAD and accelerometer are configured to acquire data at the sampling rate of 50 Hz. The data from FBGSAD is recorded simultaneously from all the 6 FBG sensors corresponding to both the feet, using a commercial FBG sensor interrogation system (Micron Optics SM-130). Since, the obtained data from the FBG interrogator is in the form of change in reflected Bragg wavelengths, a pre-determined wavelength to strain conversion factor of 1.22 pm/$\mu\varepsilon$ is used to obtain the corresponding strains from each of the sensors [56].

For quantifying the relative postural stability of the subjects under test, the real-time strain recorded from FBG sensors are compared against the calibrated tri-axial accelerometer (ADXL326) [54], [55] of 60mV/g sensitivity, which records the movements at CG of the subjects. From the obtained real time strain data, the variations in the magnitude of the data are considered for accessing the stability and balance factor of the subject. The axes system adopted in the present study for the accelerometer is shown in Fig. 4. All measurements are obtained with respect to the accelerometer's fixed axes system. The accelerometer outputs the accelerations along X, Y, and Z-axes.

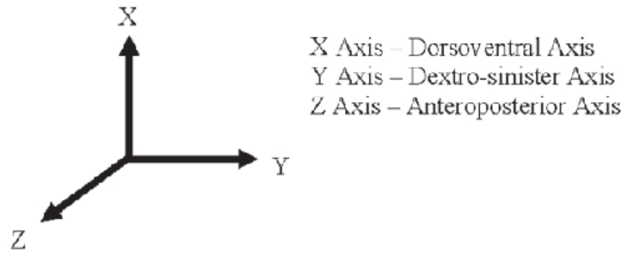

Fig. 4 Axes system used for accelerometer measurements

IV. RESULTS AND DISCUSSION

This section presents two distinct aspects of the results obtained in the study. One being the quantitate evaluation of volunteered subjects for postural stability from FBGSAD and commercial accelerometer and the other being the evaluation FBGSAD with accelerometer and other obvious facts for different cases of the experiment (BO, BC, UO and UC).

A. Subjective Evaluation for Postural Stability Using FBGSAD and Accelerometer

As ten subjects are involved in the present study, a box-plot analysis is used which summarizes all the data measured on an interval scale, helping to compare different sets of measured data values. This type of analysis represents the strain distribution, mean, median, and percentile ranges for better analysis and comparison of the measured plantar strain data among the volunteered subjects.

Fig. 5 shows the box-plot of CG variations of all the subjects for BO trial obtained from accelerometer. Fig. 6 shows the strain variations of all the subjects for BO trial obtained from FBGSAD. From qualitative comparison of the results of Figs. 5 and 6, it is evident that distribution, mean, median, and percentile ranges of individual subjects match well. From both the plots, it is evident that for BO case, the postural stability/balance results can be grouped into three categories in the order of higher to lower postural balance and stability (Group 1: sub 5, sub 8 and sub 1; Group 2: sub 4, sub 3 and sub 2; Group 3: sub 10, sub 9 sub 7 and sub 6).

For the purpose of illustration, only BO case validation has been reported in the present study. However, all the other cases (BC, UO and UC) are also analyzed with their respective acceleration variations and the results are found to be in good agreement.

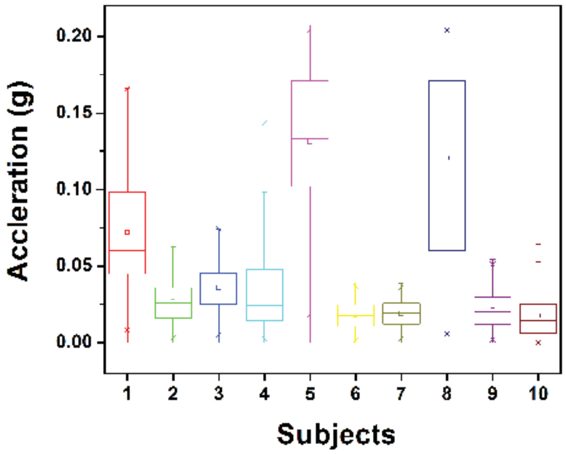

Fig. 5 CG variations of all the subjects for BO case obtained from accelerometer

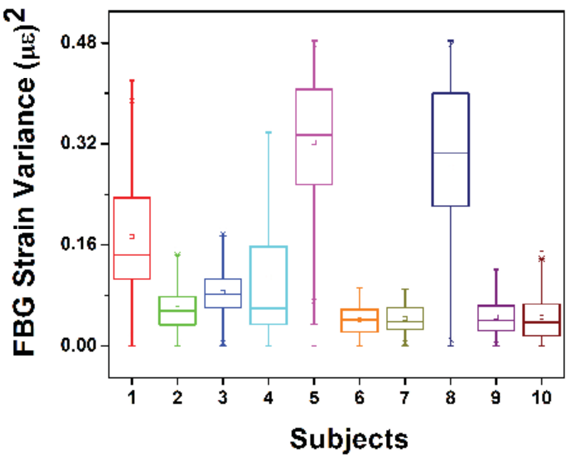

Fig. 6 Strain variations of all the subjects for BO case obtained from FBGSAD

B. Analysis of Different Cases for Validation of FBGSAD

From the real time strain recording of all the subjects (sub 1 to sub 10) of all the cases (BO, BC, UO and UC), the mean of spread of the individual case data is analyzed (excluding the 10 sec ingress and 10 sec egress of FBGSAD). This is used to arrange different cases on the order of the postural balance and stability.

Figs. 7 and 8 show the box-plot spread of mean of strain variations of all the 10 subjects for all the cases (BO, BC, UO and UC) obtained from accelerometer and FBGSAD respectively. From the quantitative observation of these plots, it is evident that subjects in BO have more stability than other cases experimented in the study. This is obvious as a subject receives visual inputs and stands on both the legs (Table I). Similarly, the order of case preference list which can be drawn from this study for the balance and stability is BO, BC, UO and UC.

It is clear from the present results that the FBGSAD developed can assist in evaluating the balance and stability of the subjects undergoing similar tests and in accessing the suitability of them for various critical professions where balance and stability plays a key role.

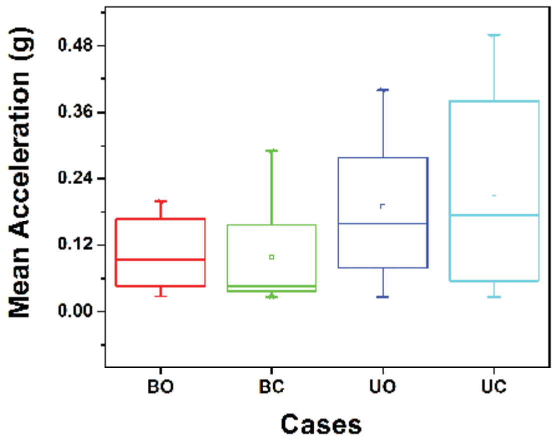

Fig. 7 Spread of mean of accelerations of all the subjects for all the cases (BO, BC, UO and UC) obtained from accelerometer

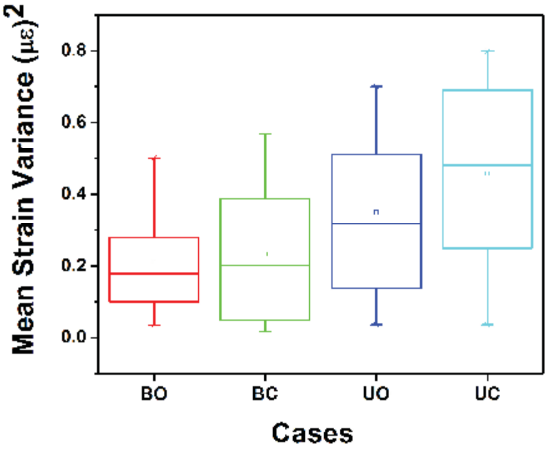

Fig. 8 Spread of mean of strain variations of all the subjects for all the cases (BO, BC, UO and UC) obtained from FBGSAD

ACKNOWLEDGEMENT

One of the authors, S. Asokan expresses gratitude to Robert Bosch Centre for Cyber Physical Systems, for partial financial support.

REFERENCES

[1] Alburquerque-Sendín F, Fernández-de-las-Peñas C, Santos-del-Rey M, Martín-Vallejo F.J, “Immediate effects of bilateral manipulation of talocrural joints on standing stability in healthy subjects.” Man Ther, 2009, vol. 14, no. 1, pp. 75–80

[2] Hahn T., Foldspang A, Vestergaard E, Ingermann-Hansen T. “One-legged standing balance and sports activity.” Scand J Med Sci Sports. 1999 , vol. 9, pp. 15–18.

[3] Laskowski E.R, Newcomer-Aney K, Smith J. “Refining rehabilitation with proprioceptive training: expediting return to play.” Phys Sports med. 1997, vol. 25, pp. 89–102.

[4] Horak F.B, “Clinical measurement of postural control in adults.” Phys Ther.1987, vol. 67, pp.1881–1885.

[5] Woollacott M, Shumway-cook A, “Attention and the control of posture and gait: a review of an emerging area of research.” Gait Posture, 2002, vol. 16, no. 1, pp. 1-14.

[6] Sartini, M, CristinaM. L,.Spagnolo A.M, P. Cremonesi C, Costaguta F, Monacelli J, Garau and OdettiP "The epidemiology of domestic injurious falls in a community dwelling elderly population: an outgrowing economic burden." The European Journal of Public Health, vol. 20, no.5, 2010, pp. 604-606.

[7] Sunderland, Ann. "Balance and gait stability following sports-related concussion." Australian Medical Student Journal vol. 2, no. 2, 2011, pp. 39-41.
[8] Bonnet, Cédrick, Claudia Carello, and M. T. Turvey. "Diabetes and postural stability: review and hypotheses." Journal of motor behavior, vol. 41, no. 2, 2009, pp. 172-192.
[9] Abu-Faraj Z. O, Hamdan T. F, Wehbi M. R, Khalil G. A, Hamdan H. M, "Design and Development of an Earthquake-Simulated Environment for the Study of Postural Stability." In Biomedical and Pharmaceutical Engineering, ICBPE 2006, pp. 188-193.
[10] Brown LA and Frank JS. "Postural compensations to the potential consequences of instability: kinematics." Gait and Posture, 1997, vol. 6, pp. 89-97.
[11] Önell A. "The vertical ground reaction force for analysis of balance." Gait and Posture, 2000, vol. 12, pp. 7-13.
[12] Sims K J and Brauer S G. "A rapid upward step challenges medio-lateral postural stability." Gait and Posture, 2000, vol. 12, pp. 217-224.
[13] Kristinsdottir EK, Fransson PA, and Magnusson M. "Changes in Postural Control in Healthy Elderly Subjects are Related to Vibration Sensation, Vision, and Vestibular Asymmetry." Acta Otolaryngology, 2001, vol. 121, pp. 700-706.
[14] Polónyová A and Hlavačka F. "Human postural responses to different frequency vibrations of lower leg muscles." Physiol. Res., 2001, vol. 50, pp. 405-410.
[15] Kelly J W, Loomis J M, and Beall A C. "The importance of perceived relative motion in the control of posture." Exp. Brain Res., 2005, vol. 161, pp. 285-292.
[16] Kuo A D. "An optimal control model for analyzing human postural balance." IEEE Transactions on Biomedical Engineering, 1995, vol. 42, no. 1, pp. 87-101.
[17] Kuo A D. "An optimal state estimation model of sensory integration in human postural balance." Journal of Neural Engineering, 2005, vol. 2, pp. S235-S249.
[18] Rocchi L, Chiari L, and Cappello A. "Feature selection of stabilometric parameters based on principal component analysis." Medical & Biological Engineering & Computing, 2004, vol. 42, pp. 71-79.
[19] Lauk M, Chow C C, Pavlik A E, and Collins J J. "Human balance out of equilibrium: non equilibrium statistical mechanics in posture control." Physical Review Letters, 1998, vol. 80, no. 2, pp. 413-416.
[20] Masani K, Vette A H, and Popovic M R. "Controlling balance during quiet standing: proportional and derivative controller generates preceding motor command to body sway position observed in experiments." Gait and Posture, 2006, vol. 23, pp. 164-172.
[21] Orell AJ, Eves FF, and Masters RSW. "Implicit motor learning of a balancing task." Gait and Posture, 2006, vol. 23, pp. 9-16.
[22] Redfern M S, Talkowski M E, Jennings J R, and Furman J M. "Cognitive influences in postural control of patients with unilateral vestibular loss." Gait and Posture, 2004, vol. 19, pp. 105-114.
[23] Syczewaska M, Dembowska-Baginska B, Perek-Polnik M, and Perek D. "Functional status of children after treatment for a malignant tumour of the CNS: a preliminary report." Gait and Posture, 2006, vol. 23, pp. 206-210.
[24] Teasdale N and Simoneau M. Attentional demands for postural control: the effects of aging and sensory reintegration." Gait and Posture, 2001, vol. 14, pp. 203-210.
[25] Morris M, Iansek R, Smithson F, and Huxham F. "Postural instability in Parkinson's disease: a comparison with and without a concurrent task." Gait and Posture, 2000, vol. 12, pp. 205-216.
[26] Geurts A C H, de Haart M, van Nes I J W, and Duysens J. "A review of standing balance recovery from stroke." Gait and Posture, 2005, vol. 22, pp. 267-281.
[27] Riemann BL. "Is there a link between chronic ankle instability and postural instability?" Journal of Athletic Training, 2002, vol. 37, no. 4, pp. 386-393.
[28] 28. Turcot, K., Allet, L., Golay, A., Hoffmeyer, P. & Armand, S. "Investigation of standing balance in diabetic patients with and without peripheral neuropathy using accelerometers." Clinical Biomechanics, 2009. vol. 24, no. 9, pp. 716–721.
[29] Shun Sasagawa. "Effect of the hip motion on the body kinematics in the sagittal plane during human quiet standing," Neuroscience Letters, 2009, vol. 450 pp. 27-31.
[30] Hasan, Samer S, Deborah W. Robin, Dennis C. Szurkus, Daniel H. Ashmead, Steven W. Peterson, and Richard G. Shiavi."Simultaneous measurement of body center of pressure and center of gravity during upright stance. Part II: Amplitude and frequency data." Gait &posture , 1996, vol. 4, no.1, pp. 11-20.
[31] Winter, David A. "Human balance and posture control during standing and walking." Gait & Posture. 1995, vol. 3, no. 4, pp. 193-214.
[32] Clark, Victoria M., and Adrian M. Burden. "A 4-week wobble board exercise programme improved muscle onset latency and perceived stability in individuals with a functionally unstable ankle." Physical therapy in sport., 2005, vol. 6, no. 4, pp. 181-187.
[33] McGuine, T. & Keene, J. "The Effect of a Balance Training Program on the Risk of Ankle Sprains in High School Athlete." The American Journal of Sports Medicine, 2006, vol. 34, no. 7, pp. 1103-1111.
[34] Omkar S.N, Ganesh D. K., Kiran P. Kulkarni, "Standing Balance: Quantification And The Impact Of Visual Sensory Input." Indian Journal of Physiotherapy & Occupational Therapy, 2009, vol. 3, no. 3, pp.44-48.
[35] Omkar S.N, Jayachandra D, Akshay S, "Stability Training and Quantification – A Essential Tool to Mitigate Space Motion Sickness," IISc Centenary International Conference and Exhibition on Aerospace Engineering, 2009, pp. 18-22
[36] Guru Prasad A. S, Omkar S. N, Vikranth H. N, Anil V, Chethana K, and Asokan S. "Design and development of Fiber Bragg Grating sensing plate for plantar strain measurement and postural stability analysis." Measurement, 2014, vol. 47, pp. 789-793.
[37] Liang Wang, Weiming Hu and Tieniu Tan. "Recent developments in human motion analysis. Pattern Recognition," 2003, vol. 36, no. 3, pp. 585-601.
[38] Veltink P H, Bussmann H B J, Vries de W, Martens W L J and Lummel van R C. "Detection of static and dynamic activities using uniaxial accelerometers." IEEE Transactions on Rehabilitation Engineering, 1996, vol. 4, pp. 375–385.
[39] Mayagoitia R E, Nene A V, Veltink P H. "Accelerometer and rate gyroscope measurement of kinematics: an inexpensive alternative to optical motion analysis systems." J Biomech., 2002, vol. 35, pp. 537–542.
[40] JosipMusić, Roman Kamnik and Marko Munih. "Model based inertial sensing of human body motion kinematics in sit-to-stand movement. Simulation Modeling Practice and Theory," 2008, vol. 16, no. 8, pp. 933-944.
[41] Kleissen R F M, Hermens H J, Exter T, Kreek J A and Zilvold G. "Simultaneous measurement of surface EMG and movements for clinical use." Med BiolEng., 1989, vol. 27, pp. 291-297.
[42] Kamnik R., J. Music´ H. Burger, M. Munih, T. Bajd, "Design of inertial motion sensor and its usage in biomechanical analysis, in: Proceedings of 4th International Conference on Electrical and Power Engineering, Isai, Romania, 2006, pp. 511–516.
[43] Mayagoitia R.E, Nene A.V, Veltink P, "Accelerometer and rate gyroscope measurement of kinematics: an inexpensive alternative to optical motion analysis system," Journal of Biomechanics, 2002, vol. 35, no. 4, pp. 537–542.
[44] Yun X., Bachmann E, "Design, implementation and experimental results of quaternion-based Kalman filter for human body motion tracking." IEEE Transactions on Robotics, 2006, vol. 22, no. 6. pp.1216–1227.
[45] Zhu R, Zhou Z, "A real-time articulated human motion tracking using tri-axis inertial/magnetic sensor package," IEEE Transactions on Neural Systems and Rehabilitation, Engineering, 2004, vol.12, no. 2, pp. 295–302.
[46] Giansanti D, Maccioni G, Macellari V, "The development and test of a device for the reconstruction of 3-D position and orientation by means of kinematic sensor assembly with rate gyroscope and accelerometers," IEEE Transactions on Biomedical Engineering, 2005, vol. 52, no. 7, pp. 1271–1277.
[47] Jurman D, Jankovec M, Kamnik R and Topic M, "Calibration and data fusion solution for the miniature attitude and heading reference system," Sensors and Actuators A, 2007, vol. 138 pp. 411–420.
[48] Lord M, Reynolds D, Hughes J, "Foot pressure measurement: a review of clinical findings," J Biomed Engg., 1986, vol. 8, pp. 283–294.
[49] Washburn R.A, Laporte R.E, "Assessment of walking behavior: Effect of speed and monitor position on two objective physical activity monitors." Res. Quart. Exerc. Sport., 1988, vol. 59, pp.83-85.
[50] Hill K.O, Fujii Y, Johnson D.C, Kawasaki B.S, "Photo sensitivity in optical Fiber wave guides: Application to reflection filter fabrication. Appl. Phys. Lett. 1978, vol. 32, pp. 647-649.
[51] Morey W.W, Meltz G, and Glenn W.H, "Fiber Bragg grating sensors." in: SPIE Fiber Optic & Laser Sensors VII, 1989, pp. 98-107.

[52] Kashyap R, “Photosensitive optical fibers: Devices and applications,” Optic. FiberTechnol., 1994, vol. 1, pp. 17-34.

[53] Hill K.O, Malo B, Bilodeau F, Johnson D.C, Albert J, “Bragg gratings fabricated in mono mode photosensitive optical fiber by UV exposure thorough a phase-mask,” Appl.Phys. Lett. 1993, vol. 62, pp.1035-1037.

[54] Batista P, Oliveira P and Cardeira B, “Accelerometer Calibration and Dynamic Bias and Gravity Estimation: Analysis, Design, and Experimental Evaluation,” IEEE transactions on control systems technology, 2011 vol. 19 pp. 1128-1137.

[55] Cavaleiro P.M, Araujo F.M, Ferreira L.A, Santos J.L, Farahi F, “Simultaneous Measurement of Strain and Temperature Using Bragg Gratings Written in Germano silicate and Boron-Co doped Germano silicate Fibers.” IEEE Phot Tech Let., 1999, vol. 11, pp.1635-37.

[56] Rao, Y. J, “In-fibre Bragg grating sensors,” Measurement science and technology, 1997, vol. 8, no. 4, pp. 355.