2013

Assessment of Postural Stability Using Inertial Measurement Unit on Inclined Surfaces in Healthy Adults

Chris Frames
Virginia Polytechnic Institute and State University

Rahul Soangra
Chapman University, soangra@chapman.edu

Thurmon Lockhart
Virginia Polytechnic Institute and State University

Recommended Citation

Bibliography

Frames, C., R. Soangra, and T. E. Lockhart. "Assessment of postural stability using inertial measurement unit on inclined surfaces in healthy adults - biomed 2013." In *Biomedical Sciences Instrumentation*, vol. 49, pp. 234-42. Research Triangle Park, NC: International Society of Automation, 2013. PMID: 23686205

Note

C. Frames, R. Soangra, and T. E. Lockhart, "Assessment of postural stability using inertial measurement unit on inclined surfaces in healthy adults - biomed 2013," in *Biomedical Sciences Instrumentation*, vol. 49 (Research Triangle Park, NC: International Society of Automation, 2013), 234-42. PMID: 23686205

Assessment of Postural Stability Using Inertial Measurement Unit on Inclined Surfaces in Healthy Adults

Published in final edited form as:
Biomed Sci Instrum. 2013 ; 49: 234–242.

Assessment of Postural Stability using Inertial Measurement Unit on Inclined Surfaces in Healthy Adults

Chris Frames, **Rahul Soangra**, and **Thurmon E. Lockhart**
Locomotion Research Laboratory, Grado Department of Industrial and System Engineering, Virginia Polytechnic Institute and State University

Abstract

Fatal and nonfatal falls in the construction domain remain a significant issue in today's workforce. The roofing industry in particular, annually ranks amongst the highest in all industries. Exposure to an inclined surface, such as an inclined roof surface, has been reported to have adverse effects on postural stability. The purpose of this preliminary study was to investigate the intra-individual differences in stability parameters on both inclined and level surfaces. Postural Stability (PS) and Limit of Stability (LOS) were assessed in seven healthy subjects (aged 25-35 years) on inclined and level surfaces using embedded force plates and an Inertial Measurement Unit (IMU). Four 90-second trials were collected on the inclined surface in distinctive positions: (1) Toes raised 20° above heel; (2) Heels raised 20° above toes (3); Transverse direction with dominant foot inverted at a lower height; (4) Transverse direction with non-dominant foot inverted at a lower height. Limit of Stability was evaluated by the two measurement devices in all four directions and margin of safety was quantified for each individual on both surfaces. The results reveal significant differences in postural stability between the flat surface condition and the inclined surface condition when subject was positioned perpendicular to the surface slope with one foot descended below the other; specifically, a significant increase was identified when visual support was interrupted. The findings lend support to the literature and will assist in future research regarding early detection of postural imbalance and preventative measures to reduce fall risks in professions where workers are consistently exposed to inclined surfaces.

Introduction

Fatal falls, slips, or trips resulted in approximately 14% of all fatal work injuries in 2011 according to the Bureau of Labor Statistics (BLS). Of the 611 fatal injuries, 541 occurred as a direct result of falls from elevation. The construction industry annually experiences the greatest incidence of fatal injuries from falls from elevation, making it the third leading cause of fatalities in industry today. Thus, interventions to deter this trend have led to considerable research in postural control strategies during task-related standing balance.

Control of balance is maintained through the integration of sensory information from the vestibular, visual, and proprioceptive systems (Diener and Dichgans, 1988; Simeonov, 2003). In familiar conditions – stable and flat support – degradation in one of the systems is compensated for by alternate feedback systems and inherent familiarization with the stable environment. For instance, lack of visual feedback on an acclimatized surface will likely result in balance maintenance, as the proprioceptive system can be relied on for balance control (Horak et al., 1989). However, in an extraneous environment, the visual decrement presents a challenge to the postural control system and an individual is at an increased risk of instability, and ultimately falls (Redfern & DiPasquale, 1997). In the construction industry, roof work environment in particular, these outcomes can be fatal. Thus, prompt recognition of the perturbed support and adequate modifications to postural control mechanisms are critical reduce worker falls.

A stable posture is described as the body's center of gravity (COG) within the base of support (BOS); the area defined by the length and width of the feet in contact with a given surface. During static postural stability, the vertical ground reaction force (COP) acts at the same horizontal location as the COG in order to maintain equilibrium and to remain within the maximum stability area, i.e., the BOS. Any deviation from the BOS will theoretically result in a compensatory step/loss of balance. Accordingly, an individual's limits of stability (LOS), commonly referred to as functional stability limits (FSL), refers to the maximum distance one can volitionally displace their COG, and lean his/her body in a given direction without losing balance, stepping, or grasping (Holbein & Chaffin, 1997; Holbein & Redfern, 1997). FSLs in several directions combine to represent the functional stability region (FSR), or stability limits area. This area, a region within the BOS, is often smaller than the theoretical area due to limiting ankle strengths, internal postural control abilities, surface conditions, and other factors (Holbein 1993). Thus, FSLs could be used to help predict when compensatory stepping is needed, and what directions or strategies may be most effective to regain balance. In fact, this area is likely to be an important prerequisite for the successful planning and execution of movements such as performing manual tasks on varying surfaces and inclinations, and bending over from standing position to pick up an object from the floor.

Accordingly, in the Hsiao & Simeonov (2001) study, the authors identified various factors that affect workers' balance and increase the likelihood of falls: environmental, task-related, and personal. Apropos to the present study, our investigation primarily focused on the multitude of associated environmental and task-related factors that can affect worker balance. Environmental factors, such as slope inclination, surface symmetry, friction, and visual references and interactions, can all hinder worker postural stability. Regarding task-related (physical performance factors), muscular fatigue is the pervading performance criteria that negatively affects the proprioceptive system inducing lower limb fatigue and ultimately instability.

It is well-known that increase in friction demand elicited by increased surface inclination decreases biomechanical parameters associated with walking, but the actual effect of the inclination on balance control, especially static standing posture, is limited (McVay & Redfern 1994). Furthermore, the few studies that have addressed surface inclination with standing balance, have typically investigated the affects and subsequent measurements post-surface inclination tasks. For instance, Wade and Davis (2009) investigated fatigue-related affects following duration of an inclined task with postural stability parameters measured on a flat force plate-embedded surface. Alternatively, the present study primarily focused on standing balance measures in real-time during a flat and inclined surface tasks.

Current protocols for clinical measurements require a laboratory setting for data collection utilizing a force plate. While this environment is conducive for a more controlled setting (especially visual references and interactions), it loses some of the variability associated with real-time performance task in a natural environment. With this in mind, the objective of this study was to investigate the effects surface slope and visual feedback degradation had on standing balance in construction roof-related tasks with inertial measurement units. In addition, limits of stability were determined on each support surface and direction to determine the support conditions conducive to optimal balance control. Understanding these underlying causes and effects will be useful in developing effective prevention strategies to reduce the incidence of falls from roofs.

NIH-PA Author Manuscript

NIH-PA Author Manuscript

Methods

Subjects

Seven healthy young adults (6 male and 1 female) volunteered to participate in this study. Subject age range was from 26 to 32 years (mean age = 27.3 years). Basic body function data was collected including, height (mean = ~ 175 cm), weight (mean = 73.4 kg), and dominant foot (all subjects were right foot dominant). Prior to the study, all participants gave informed consent and answered a brief questionnaire inquiring about their medical history and ability to perform standing postural balance trials for 3-minutes.

Data Collection Protocol

Data were collected for each participant in 90 min sessions. Each participant was given standardized shoes provided by the lab. During the testing, participants were instructed to take a comfortable stance on the flat and inclined surfaces. To standardize the foot position throughout testing, the participant's most anterior and posterior aspects of both feet, and the lateral portions of the forefoot and rear foot were marked and located to define the BOS limits.

Prior to the commencement of the experiment, subjects were given a brief familiarization period with both the flat surface and the inclined plane. Regarding the normal surface, a particular focus was on familiarizing the subject with the LOS test itself; with the intention of collecting optimal performance limits. Practice trials were given on the inclined surface for PS trials and LOS trials in all four-directions, so the participants could gain experience, and more importantly, determine the amount of fatigue involved and the varying limbs affected – i.e., participant performing PS trials lateral to the incline plane would have to adopt a stance that required the limb contralateral to the limb higher up the incline, to bear the majority of the weight; a significant amount of fatigue is involved in this stance. Likewise, physical exertion and muscular fatigue has been reported to occur during balance control on inclined surfaces (Gauchard et al., 2001; Nardone et al., 1997). Each test was conducted with the subjects positioned in a standardized position (reference tape was placed on the floor) for all four directions on the inclined surface (and the trials on the normal surface).

Apparatus

An inclined surface structure, measuring approximately 4-ft in height at a 20° incline, was appended perpendicular to a flat (0°) walkway in the Locomotion Research Laboratory at Virginia Tech. This pitch angle was determined in accordance with previous investigations (Simeonov et al., 2003) and by the Occupational Safety and Health Administration (OSHA) – OSHA classifies 4/12 (~ 18°) as a low-sloped roof and 6/12 (~ 26°) as steep-sloped. Therefore, we opted for a slope surface angle in between a low-sloped and steep-sloped angle; a pitch that roof workers commonly perform tasks on without any additional support devices. An Inertial Measurement Unit (IMU) system harnessed to the trunk of the subject, was utilized to quantify both postural stability measurements and LOS tests. The IMU consists of a MMA7261QT tri-axial accelerometer, an IDG-300 gyroscope (x and y plane) and an ADXRS300 gyroscope (z-plane uniaxial).

Limits of stability (LOS)

Participants stood upright on a 20° inclined surface with their feet approximately shoulder width apart and arms at their sides – regarding flat surface tests, feet were placed a little wider (shoulder width apart) than the standard LOS test procedure, to compensate for LOS on an incline plane with length of foot perpendicular to the slope of plane and dominant foot ascended/descended above/below the weaker. The tests closely followed the protocol described by Holbein-Jenny et al. (2003). Participants were instructed to keep their body rigid and lean right, left, forward and backward as far as possible; they were to maintain the full plantar surface of their feet in contact with the floor surface and remain in each extreme position for approximately 2-3 seconds. Two LOS trials were performed in each of the five positions (Figure 1): *1. Flat surface (LOS); 2. Transverse direction of inclined surface with dominant foot at the lowest position (LOSF); 3. Foot plantar-flexed with heels raised 20° from the toes facing away from the incline (LOSR); 4. Transverse direction of (lateral to inclined surface) with weaker foot at the lowest position (LOSB); 5. Toes raised 20°, length of foot parallel to the surface facing the inclined plane*. To control for foot length, the stability limits were calculated and computed as the peak AP and ML limits as a percent of subject foot length.

Postural stability (PS)

Participants stood upright on a flat and inclined surface, for 90-seconds with their feet shoulder width apart. Dependent variables were the average velocity of COP sway, and the COP sway area. Given that two trials of PS are considered to be a reliable estimate of PS (Lafond et al., 2004), the average of the two trials were used for analysis.

The testing conditions were the following (Figure 1): (1) eyes open and closed-flat surface (PSOpen & PSClose); (2) eyes open-inclined surface with dominant foot descended below the weaker (IPSOpenF), (3) eyes open and closed-inclined surface with heels 20° above toes (PSOpenR & PSCloseR); (4) eyes open and closed-inclined surface with dominant foot ascended above the weaker foot (PSOpenB & PSCloseB); (5) eyes open and closed-inclined surface with toes 20° above the heels (PSOpenL & PSCloseL). The postural stability-testing conditions were chosen to reflect the variety of visual and support surface conditions encountered by workers during the course of their work-related activities. To standardize the visual conditions during the eyes open protocol conditions, the force plate was positioned directly in front of a monitor with a colored dot and participants were asked to look directly ahead at it during the postural stability-testing conditions.

Dependent measures

The values of the dependent variables were derived from the COP movement in both flat (one-direction) and inclined surfaces (four-directions). The variables were the sway velocity, and COP sway area. Sway velocity (m/s), is a measure of the angular change of the COP per unit time, where the value is representative of changes in the location of the COP in the anterior, posterior, medial, and/or lateral directions. Higher values indicate decreased postural stability, as they imply larger angular changes in the location of the COP. Previous research has identified sway velocity as an appropriate dependent measure for use in determining postural stability (Wade et al., 2004). Dependent measures in the LOS tests included maximum COP displacements in the AP and ML directions.

Data Analysis

Analysis of variance was used to determine if the independent variables affected the dependent measures. Tukey's honestly significant difference (HSD) tests were used to group the postures into significantly different subsets. A 0.05 significance level was applied throughout all the statistical analyses. Data were analyzed separately for each lean direction.

NIH-PA Author Manuscript

NIH-PA Author Manuscript

Results

Limits of stability (LOS)

COP-Displacement—A one-way ANOVA measuring significant differences between AP and ML COP-displacements and the 5 LOS support surface conditions were compared. No significant differences were found between the surface conditions and the COP-displacements (Figure 2). Interestingly, although not significant, the greatest AP COP-displacement (0.07 m) occurred in position 2, when the subject's dominant lower extremity was straight and descended below the non-dominant foot. Moreover, the greatest ML COP-displacement occurred in a similar position with except that the dominant lower extremity was now ascended further up the incline than the non-dominant foot. In this position (4 in Figure 1),

Postural Stability (PS)

Sway Velocity—Analysis of variance with a 0.05 significance level, revealed no significant differences between the sway velocities in quiet standing postural measurements. Furthermore, the post-hoc Tukey's-HSD test found that the supporting conditions compared with eachother were not significantly different.

Sway Area/Range—One-way ANOVA tests for the varying independent measures revealed significant differences in two of the support surface conditions: PSOpen on the flat surface compared with PSCloseF on position 2 (Figure 1) of the inclined support surface; PSOpen on the flat surface compared with PSCloseB on position 4 (Figure 1) of the inclined support surface.

Discussion

The findings demonstrate that certain roof support surfaces increased worker standing postural instability. In particular, when the subject stood so that the length of their foot was effectively perpendicular to the surface slope in positions 2 and 4 of Figure 1, respectively (slight eversion and inversion of both ankles in positions), a significant increase in postural sway occurred compared with postural stability measures on the flat surface. The outcome of this slope characteristic suggests that the altered visual and proprioceptive feedback that occurs with the challenging stance orientation, reduces the base of support. The ankle position and ankle musculature is compromised in positions 2 and 4, because in order to maintain ones COG within the BOS, the ankle joints must be inverted/everted; thus, the increased muscle activity of the lower limbs likely decreases postural stability (Maki, Holliday and Fernie, 1990; Nardone et al., 1997; Vuillerme et al., 2002). This reasoning, specifically effects of fatigue on joint proprioception, is thought to be the primary factor involved with the increase in sway measures on inclined support surfaces (Chabran et al., 2002; Corbeil et al., 2003).

The subjects were able to perceive the destabilizing effects of the surface inclination and height when they could rely on visual input in all four positions on the inclined surface. However, when they were oriented in positions 2 and 4, which require one leg to be straight and the other leg slightly flexed, and were cut off from visual references, they were unable to maintain a postural sway area congruent with results attained on the flat surface. This suggests that the amplified effects placed on the proprioceptive and the vestibular system when an individual is standing in positions 2 and 4 of a surface inclination is much greater than when an individual is oriented in the other positions. It's likely that the increase in physical exertion, and thus the ensuing fatigue, is due in large part to the stance and body configuration that one must adopt in order to maintain balance across an inclined surface. In addition, given that one leg is situated at a greater height above the other, the lower foot is burdened with the majority of the weight. Here, all three sensory systems are necessary to reduce instability in such a compromising environment.

Prior to the experimental trials we hypothesized that as a result of the reduced effective BOS involved with the inclined support surface, that the LOS tests comparing positions 2 and 4, with the flat surface LOS tests would reveal significant differences in stability limits – this was not the case. Analysis of variance and AP- and ML-COP displacements in all five support conditions did not elicit a significant decrease in functional stability region compared to one's theoretical region (BOS by foot measures). Depending on how the subjects were oriented on the incline, they compensated for the limited range of motion in one direction by adopting a greater COP displacement in the opposing direction.

There were several notable limitations to this study. First and foremost, validation of IMU data results, were not compared with force plate measurements, as collection errors forced the researchers to eliminate it from the analysis. While quantification of postural stability using portable, accelerometer-based devices has been used extensively as a standalone measurement device, it would be beneficial to compare the data with known force plate values. In particular, during positions 2 and 4 of PS and LOS tests, subjects were allowed to bend the knee of the extremity highest up the incline (10° – 20°), simply because it is impossible to perform standing balance measurements using established criteria, i.e., keeping the aforesaid limb straight. How much this strategy altered the results of these two positions in comparison with the other support surface conditions is not known. Another important limitation was the low sample size and lack of gender variation.

The extent to which these results can be generalized is limited by the experimental task criteria and duration of exposure. For instance, participants in the study were only required to stand in a static posture for a finite period of time. How this experimental task compares with real roof work tasks is not determinable at this stage in our preliminary investigation. Accumulating more subjects, documenting the relevant findings, and subsequently validating the accelerometer's results with established force plate analyses will greatly expand our knowledge on the subject. Further, future research involving more dynamic tasks, such as reaching in various directions or holding an object will help put the surface environmental factors into greater context.

Conclusion

Inclined surfaces in the construction and roof work environments, induced a significant increase in postural instability when the subjects were positioned across the surface slope (long axis of the foot was perpendicular to the slope so that feet were not level during measurement tasks) without visual guidance. These findings reveal that an individual is able to optimally control standing balance in each of the four positions on the inclined surface. However, when visual support is impaired, instability occurs on positions 2 and 4 of Figure 1, and as a result subjects' COP radius and sway area are significantly different to the values obtained on non-inclined surfaces. Interestingly, LOS tests revealed no significant differences in stability regions even though at least one side of the LOS sway task was severely hindered by the environmental constraints – facing the inclined slope with 20° dorsiflexion in both feet, subjects are only really able to displace their Anterior-Posterior COP in the anterior direction because of the physical and proprioceptive demands placed on the dorsiflexed ankles of the lower limbs.

Practical implications are too rudimentary to implement in any established work criteria, but the findings can potentially be utilized to increase worker awareness when task requirements place them in compromising environmental conditions. For instance, a worker will be made aware that balance is most vulnerable when they're stood perpendicular to the roof surface inclination and visual field is impaired; hence, they should take care not to perform any additional maneuvers that add additional strain to the fully attuned sensory systems. Incidentally, whether that additional strain is something as simple as holding an object or the onset of fatigue, requires further research and a larger amount of test subjects.

Accordingly, the use of portable accelerometers to measure postural stability in inclined surface scenarios may be the greatest practical implication of the study, but as a result of our contaminated force plate data, validation for the accelerometer results leave a lot to be desired. However, with additional research and greater reliability between the two devices, the accelerometer can potentially be utilized outside the laboratory and in actual work environments, where additional factors can be accounted for, such as wind and temperature. Thus, the ultimate goal of this preliminary research is the design and implementation of an intervention protocol or ideally an everyday smartphone device that can measure and actively intervene in situations when an individual's stability limits are under threat.

References

Bureau of Labor Statistics: US Department of Labor. Fatal occupational injuries by industry and event or exposure. 2011a.

Chabran E, Maton B, Fourment A. Effects of postural muscle fatigue on the relation between segmental posture and movement. J Electromyogr Kinesiol. 2002; 12(1):67–79. [PubMed: 11804813]

Corbeil P, Blouin JS, Begin F, Nougier V, Teasdale N. Perturbation of the postural control system induced by muscular fatigue. Gait Posture. 2003; 18(2):92–100. [PubMed: 14654212]

Diener HC, Dichgans J. On the role of vestibular, visual and somatosensory information for dynamic postural control in humans. Progress in Brain Research. 1988; 76:253–262. [PubMed: 3064150]

Gauchard G, Chau N, Mur JM, Perrin P. Falls and working individuals: role of extrinsic and intrinsic factors. Ergonomics. 2001; 44(14):1330–1339. [PubMed: 11900422]

Holbein-Jenny MA, McDermott K, Shaw C, Demchak J. Validity of functional stability limits as a measure of balance in adults aged 23–73 years. Ergonomics. 2007; 50(5):631–646. [PubMed: 17454084]

Holbein-Jenny, MA.; Stinson, AT.; Niederklein, RW.; Bechtel, ME.; Elmer, JR.; Richardson, TL. Functional stability limits during reaching tasks. Proceedings of the Human Factors and Ergonomics Society 47th Annual Meeting; Santa Monica, CA: Human Factors and Ergonomics Society; 2003. p. 1141-1144.

Holbein MA, Redfern MS. Functional stability limits while holding loads in various positions. International Journal of Industrial Ergonomics. 1997; 19:387–395. [PubMed: 11540602]

Horak FB, Shupert CL, Mirka A. Components of postural dyscontrol in the elderly: a review. Neurobiol Aging. 1989; 10(6):727–738. [PubMed: 2697808]

Hsiao H, Simeonov PI. Preventing falls from roofs: A critical review. Ergonomics. 2001; 44:537–561. [PubMed: 11345496]

Lafond D, Corriveau H, Hébert R, Prince F. Intrasession reliability of center of pressure measures of postural steadiness in healthy elderly people. Arch Phys Med Rehabil. 2004; 85:896–901. [PubMed: 15179642]

Maki BE, Holliday PJ, Fernie GR. Aging and postural control. A comparison of spontaneous- and induced-sway balance tests. J Am Geriatr Soc. 1990; 38(1):1–9. [PubMed: 2295764]

McVay EJ, Redfern MS. Rampway safety: Foot forces as a function of rampway angle. American Industrial Hygiene Association Journal. 1994; 55:626–634.

Nardone A, Tarantola J, Giordano A, Schieppati M. Fatigue effects on body balance. Electroencephalogy Clin Neurophysiol. 1997; 105(4):309–320.

NIH-PA Author Manuscript

NIH-PA Author Manuscript

Occupational Safety and Health Administration. OSHA Directives — STD 3.1A. Washington, DC: U.S. Department of Labor; 1999. Plain language revision of OSHA Instruction STD 3.1, interim fall protection compliance guidelines for residential construction. Retrieved January 23, 2003, from http://www.osha.gov

Patton J, Pai Y-C, Lee WA. Evaluation of a model that determines the stability limits of dynamic balance. Gait and Posture. 1999; 9:38–49. [PubMed: 10575069]

Patton J, Lee WA, Pai Y-C. Relative stability improves with experience in a dynamic standing task. Experimental Brain Research. 2000; 135:117–126.

Pai Y-C, Patton J. Center of mass velocity-position predictions for balance control. Journal of Biomechanics. 1997; 30:347–354. [PubMed: 9075002]

Simeonov PI, Hsiao H, Dotson BW, Ammons DE. Control and perception of balance at elevated and sloped surfaces. Human Factors. 2003; 45(1):136–147. [PubMed: 12916586]

Vuillerme N, Danion F, Forestier N, Nougier V. Postural sway under muscle vibration and muscle fatigue in humans. Neurosci Lett. 2002; 333(2):131–135. [PubMed: 12419498]

Van Wegen EEH, Van Emmerik REA, Riccio GE. Postural orientation: age-related changes in variability and time-to-boundary. Human Movement Science. 2002; 21:61–84. [PubMed: 11983434]

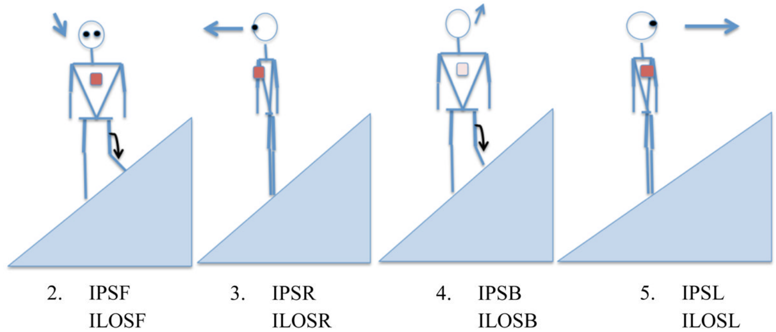

Figure 1.

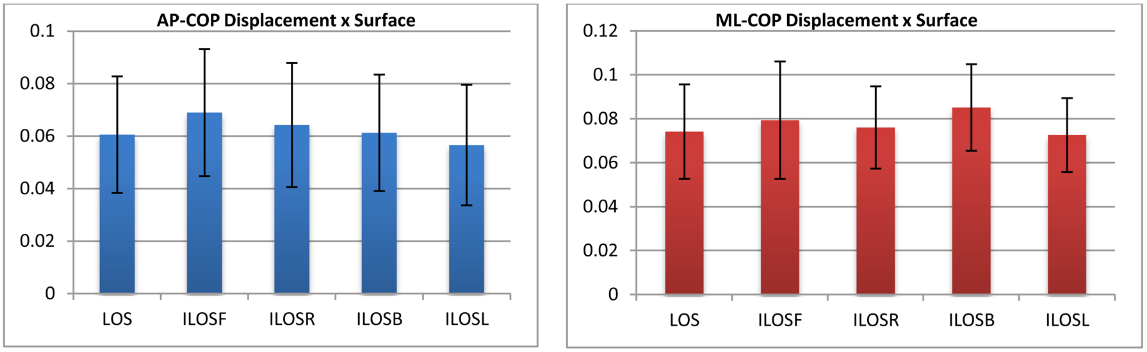

Figure 2.
COP-displacements in the anterior-posterior direction and the medial-lateral direction in ally five surface support conditions.

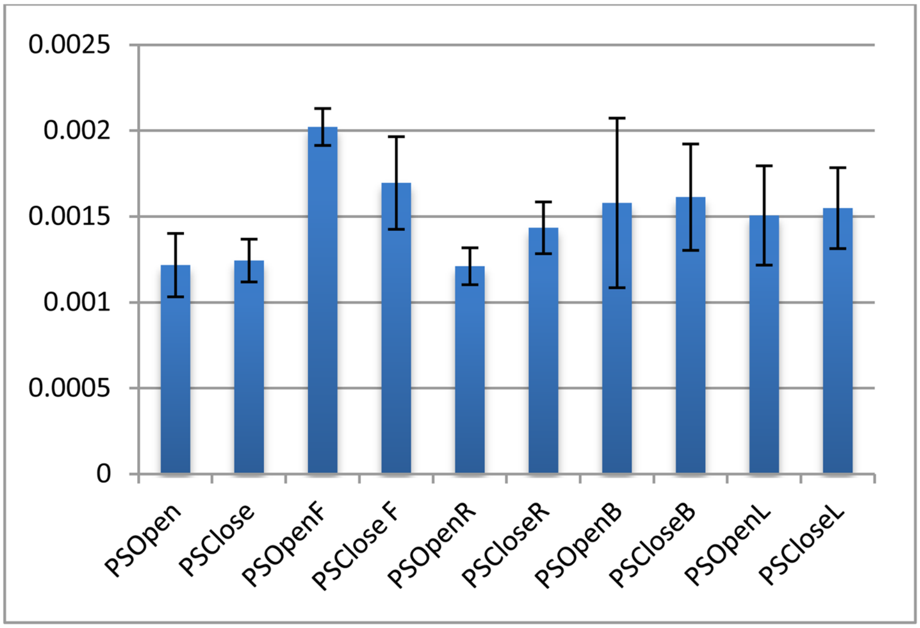

Figure 3.
Sway velocity (m/s)

NIH-PA Author Manuscript

NIH-PA Author Manuscript

Table 1

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
PSClose F	PSOpen	0.0005051	0.000153	5.01E-06	0.0010053	0.0458
PSCloseB	PSOpen	0.000503	0.000153	2.84E-06	0.0010031	0.0476
PSClose F	PSClose	0.0004951	0.000153	-5.04E-06	0.0009952	0.0546
PSCloseB	PSClose	0.0004929	0.000153	-7.22E-06	0.000993	0.0567