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Abstract

The purpose of the study was to investigate the effects of the ankle angular position and standing surface type on static upright balance. Ten young adults stood on a force platform or on a firm wedge that induced 15° of either dorsiflexion or plantarflexion. A piece of foam was placed on top of the force platform and on the wedge. The center of pressure (COP) distance and velocity in the anteroposterior (AP) and mediolateral directions were calculated. Significantly larger magnitudes in most of the investigated variables were seen while standing with ankles in the dorsiflexion when compared to standing naturally ($p<0.05$). Plantarflexion increased the COPAP velocity substantially when compared to a natural stance. Standing on the foam surfaces resulted in increases in all of the COP measures in all of the ankle conditions.

Keywords: dorsiflexion, plantarflexion, proprioception, standing balance

Introduction

The central nervous system assimilates afferent sensory inputs from the visual, proprioception, and vestibular systems in order to maintain a stable bipedal stance (Ivanenko and Gurfinkel, 2018; Massion, 1994). When standing still, the vertical projection of the center of gravity rests anteriorly to the axis of the ankle joints (Le Huec et al., 2011), which requires the plantar flexors (gastrocnemius and soleus) to function as agonists in order to prevent one from falling forward (Di Giulio et al., 2009; Shumway-Cook, 2012; Winter et al., 1998). Moreover, the proprioceptive inputs from the plantar and dorsiflexor muscles of the ankle regulate postural sway in the sagittal plane (Di Giulio et al., 2009; Loram et al., 2005). The Golgi tendon organs (sensitive to muscle tension) and muscle spindles (responsive to changes in the length of the muscle fibers and joint rotation) encode changes in each muscle length, providing the important proprioceptive information needed to maintain balance (Kistemaker et al., 2012; Proske, 2006). Thus, maintaining an upright stance that alters the ankle muscle lengths can be associated with mechanical and proprioceptive challenges.

Standing over an inclined surface is common when performing daily activities, such as overhead reaching and cleaning. It is also common in the construction industry because these workers perform many tasks while maintaining their balance over inclined surfaces. Moreover, standing and walking over inclined surfaces, which are regular activities of roofers, could be associated with a diminished ability to perceive proprioceptive information, and as a result, could be a contributing factor to the increased risk of work-related incidences. Indeed, falls from roofs account for the majority of work-related injuries in the US (Bureau of Labor, 2016).

Prior studies have examined the effects of standing on surfaces that change the angular position of the ankle joint on postural control. For instance, standing on laterally oriented wedges (ankle eversion) improved postural control while standing still (Ganesan et al., 2014) and when dealing with external perturbations (Lee et al., 2017). However, standing on inclinations with dorsiflexed or plantarflexed ankles resulted in diminished postural control (da Costa Barbosa and Vieira, 2017; Garkavenko et al., 2012; Lin and Nussbaum, 2012; Mezzarane and Kohn, 2007). Moreover, it was reported previously that standing on soft surfaces reduced the accuracy of the information obtained from the plantar cutaneous receptors of the feet and increased the postural sway while standing in a natural ankle position (Chiang and Wu, 1997; Isableu and Vuillerme, 2006; Maitre and Paillard, 2016; Patel et al., 2008; Tanaka and Uetake, 2005; Vuillerme and Pinsault, 2007). However, to the best of our knowledge, the effects of standing with dorsiflexed and plantarflexed ankles on soft surfaces on the upright postural stability have not been investigated.

Thus, the aim of this study was to evaluate postural control using tasks that modified the proprioception of an upright stance at two levels: ankle muscle proprioception (standing on wedges) and plantar cutaneous input proprioception (standing on foam). We hypothesized that standing on a wedge that induced the ankle joints into dorsiflexion or plantarflexion positions would be associated with increased postural sway when compared to standing with the ankle joints in a natural position. We also hypothesized that standing on a foam surface would be linked with increased postural sway when compared to standing on firm surfaces, regardless of the ankle joint positions. These hypotheses were tested using an experimental paradigm allowing the manipulation of the angular positions of the ankle joints (standing on a flat surface or a wedge inducing dorsiflexion or plantarflexion) and the accuracy of the plantar cutaneous proprioceptive information (standing on a firm surface or a foam surface).

Methods

Participants

Ten healthy subjects, eight males and two females, between the ages of 24 and 29 years old (mean age 26±1.5 years, mean height 166±6.1 cm, and mean weight 62.5±14.5 kg) participated in this study. Prospective participants with musculoskeletal deformities or taking medications, such as antidepressants or sedatives, were excluded. The University of Illinois at Chicago Institutional Review Board approved this study, and a consent form was signed by each subject prior to participation.

Experimental setup and procedure

A 40×40 cm rigid wedge that could induce 15° of dorsiflexion or 15° of plantarflexion was constructed using plywood. Each subject was asked to stand with his or her eyes open, barefoot, with his or her feet shoulder width apart on top of a force platform [Model OR-5; Advanced Mechanical Technology, Inc. (AMTI), Watertown, MA, USA] (natural stance) and over a rigid wedge placed on top of the force platform, which induced either dorsiflexion or plantarflexion (Fig. 1). A 40×40×10 cm piece of foam (Balance Master; NeuroCom International Inc., Clackamas, OR, USA) was placed on top of either the force platform or the wedge. While standing, each subject was instructed to maintain an erect and steady posture with his or her upper extremities along the body (with the palms towards the body) and head in a neutral position and his or her knees and back straight. The subjects were also asked to look at a marker placed 100 cm in front of them at eye level. Each subject was provided with one practice trial for each condition before the actual data collection began. The subjects were also given a five-minute rest in the middle of the experiment and when needed in order to avoid fatigue. A harness system that was loosely attached to the ceiling was used throughout the experiment for safety. It was reported that a safety harness does not interfere with the evaluation of postural sway in standing (Freitas et al., 2005).

Two trials were collected per condition, and each trial lasted for 30 seconds. The body position during experiments was checked by the experimenter and if there were recognizable changes in the knee and hip angle joints positions or the subjects moved their upper limbs in order to maintain balance, the trial was repeated. The order of the conditions was randomized for each subject in order to minimize learning effects. In the following text, the experimental conditions were abbreviated in reference to the ankle joint angular positions [natural stance, horizontal (H); toes-up, ankle dorsiflexion (D); and toes-down, ankle plantarflexion (P)] and the type of contact surface [firm (F) and soft (S)].

The force platform signals were digitized with 16-bit resolution at 1000 Hz by means of an analog-to-digital converter and customized LabVIEW 8.6.1 software (National Instruments, Austin, TX, USA), and they were stored on a computer for further processing.

<Fig. 1>

Data processing

The vertical component of the ground reaction force (Fz), the horizontal components in the anteroposterior (AP) direction (Fy) and in the mediolateral (ML) direction (Fx), and the moments of force around the sagittal (My) and frontal (Mx) axes were analyzed using MATLAB software R2016a (MathWorks, Natick, MA, USA). The data were filtered using a second-order zero phase Butterworth low-pass filter with a cut-off frequency of 20Hz. The time-varying center of pressure (COP) displacements in the AP direction (COPAP) and ML direction (COPML) were calculated.

The average of the COP distance in the AP and ML directions were subtracted from the respective mean COP outcomes. Then, the COP mean distances were calculated as the average of the absolute values of the COPAP and COPML time series respectively, and they represented the average AP or ML distance from the mean COP. Additionally, the COPAP and COPML velocities were calculated as the total COP excursion divided by the time in the AP and ML directions separately (Prieto et al., 1996).

Statistical analysis

The COP distance and velocity in the AP and ML directions were analyzed using a two-way repeated measures ANOVA [(3 ankle positions: H, D, and P) × (2 surface types: F and S)]. A post-hoc analysis with a Bonferroni correction was used when appropriate. A p value of less than 0.05 was considered to be statistically significant, and the analyses were carried out using IBM SPSS Statistics for Windows software (IBM Corp., Armonk, NY, USA). The COP variables are presented as the mean ± standard deviation unless otherwise indicated.

Results

Larger COP outcomes were seen in the dorsiflexion stance (D) when compared to the plantarflexion (P) and natural stances (H). There was an increase in the COP values obtained when standing on the soft surface (S) when compared to standing on the firm surface (F) for all of the ankle conditions (Table 1). The statistical analysis revealed no interactions between the ankle positions and the surface types in any of the variables studied ($p>0.05$). It also yielded a main effect of the ankle positions and a main effect of the surface types in all of the COP values ($p<0.05$), as demonstrated in Table 1. The COPAP velocity (mm/s) exhibited the largest magnitude of increase when subjects stood over the inclined surfaces D and P among all variables. In the different ankle positions, the COPAP velocity averaged over the two surfaces types (F and S) increased from 24.2 mm/s in the H stance to 38.7 mm/s in the P stance and 47.2 mm/s in the D stance (Fig. 2). Correspondingly, the post-hoc results indicated a significant difference in the COPAP velocity between H×D ($p<0.01$) and H×P ($p<0.05$), respectively (Fig. 2). Similarly, COPML velocity showed the largest value in D condition and it was significantly larger in comparison to the H or P condition (both $p<0.01$) (Fig. 2). D stance also induced a larger COP distance when compared to P and H in the AP and ML directions, and the increase was significant between H×D for the COPML distance ($p<0.01$) (Fig. 2).

Standing on the soft surfaces increased the magnitude of the COP variables when compared to standing on the firm surfaces in all of the ankle conditions. The COP values that were calculated while standing on the firm and soft surfaces averaged over the three ankle positions are shown in Figure 3. Substantial differences between standing on the firm and soft surfaces for all of the investigated COP variables (all $p<0.01$) could be seen. When standing on the soft surfaces, the highest magnitude of increase in all of the COP variables was observed in the H condition followed by the P and D conditions. For instance, while standing on the soft surface, when compared to standing on the firm surface, the COPAP distance increased from 9.7±2.6 mm to 17.8±5.1 mm in the H condition, from 15.7±8.7 mm to 18.9±4.4 mm in the D condition, and from 11.5±3.3 mm to 14.3±1.8 mm in the P condition (Table 1).

< Table 1 >

< Fig. 2 >

< Fig. 3 >

Discussion

The purpose of this study was to investigate the effects of standing on wedges that induced 15° of dorsiflexion or plantarflexion at the ankle joints. It is important to note that the subjects were all able to follow the instructions (maintaining an erect posture with the head in a neutral position and knees and back straight) in all of the experimental conditions. Because of this, the body alignment in relation to the gravity line was almost the same in all of the conditions, suggesting that the vestibular information was not affected. The results of the study demonstrated that the postural sway increased when the subjects stood on the wedges when compared to standing with their ankle joints in the natural position, and as such, our first hypothesis was supported. Moreover, we observed increased magnitudes in the COP outcomes in the conditions of standing on soft surfaces when compared to standing on firm surfaces, which supported our second hypothesis.

Role of the ankle joint position

Three experimental conditions involving standing with a natural stance and with the ankles in plantarflexion and dorsiflexion were implemented in our study. Standing in a natural stance requires the activation of the plantar flexors in order to maintain an upright posture, while the ankle dorsiflexors are mostly inactive (Di Giulio et al., 2009). A plantarflexion stance increases the tibialis anterior muscle length moderately, and it elicits substantial activation of the calf muscles, while the dorsiflexion stance increases the activation of the tibialis anterior, and it stretches the calf muscle to its submaximal length (Mezzarane & Kohn, 2007). Standing with the ankles in plantarflexion or dorsiflexion could potentially affect the body alignment, which, in turn, can affect the standing balance. However, we believe this was not the case because all of the subjects followed the instructions and maintained an upright posture with fully extended knees and hips and a straight trunk in all three ankle positions.

There was a dramatic increase of the COP magnitudes observed in the dorsiflexion stance when compared to the plantarflexion and natural stances. It is important to note that the subjects were asked to stand with a 15° dorsiflexed ankle, almost reaching the ankle dorsiflexion maximum range of motion that varies between 15° to 20° (Roaas and Andersson, 1982; Soucie et al., 2011). Moreover, because the gastrocnemius crosses the knee joint, it contributes to the knee flexion adjustment: a stance with stretched calf can also increase the stiffness of the knee joints and increase postural uncertainty at the knee joint (Li et al., 2002; Marieb et al., 1998). Thus, the mechanical challenge of a dorsiflexion stance can contribute to an increased COP magnitude.

The plantarflexion stance was relatively stable with a significant increase in the COPAP velocity, which is in line with the earlier findings (da Costa Barbosa and Vieira, 2017; Lin and Nussbaum, 2012). Moreover, it was reported that the plantarflexion stance is associated with an increase in the soleus muscle activation, and it was reasoned that the calf muscle activity might result in a noise-like fluctuation in the ankle joint torque in order to sufficiently control the COP oscillations (Mezzarane & Kohn, 2007). Our results suggested significant increases in only the COPAP velocity in the plantarflexion condition. Likewise, previous studies that investigated the effects of high heeled shoes on postural stability showed outcomes similar to ours: wearing high heeled shoes doubled the COPAP velocity (Gefen et al., 2002; Gerber et al., 2012; Mika et al., 2016). It might be that the COPAP velocity reflects an excessive postural correction to restrict the forward sway of the body.

Effects of the modified proprioceptive information on the postural balance

Standing with dorsiflexed ankles might be associated with an additional proprioceptive challenge. It was argued in the literature that the muscle spindles of the tibialis anterior, when compared to the calf muscles, play dominant roles in encoding the ankle joint rotation in the natural stance (Di Giulio et al., 2009). Those researchers reasoned that the inactive nature of the tibialis anterior in natural stance facilitates the function of its spindles to track the changes in the ankle joint rotation. Other investigators reported a similar negligible magnitude of activity in the tibialis anterior muscle in both the plantarflexion and natural stances (Mezzarane and Kohn, 2007; Sasagawa et al., 2009). Nevertheless, there was a co-activation of the tibialis anterior and calf muscles associated with the dorsiflexion stance over 14° inclined surface (Mezzarane and Kohn, 2007). Such activation pattern might introduce a noise in the muscle spindle afferent inputs and diminish the upright balance (Burke et al., 1978; Di Giulio et al., 2009; Mezzarane and Kohn, 2007; Wise et al., 1999; Yamagata et al., 2019).

We also reported an increase of the COP magnitudes while standing on the foam surfaces when compared to the standing on the firm ones. Standing over inclined surfaces necessitates different pressure distribution under the feet, which might shift the location of the foam tactile stimulus (Garkavenko et al., 2012). Nevertheless, the outcomes indicated a significant main effect of the surface for all of the COP variables which is line with the findings of the previous studies (Chiang and Wu, 1997; Isableu and Vuillerme, 2006; Maitre and Paillard, 2016; Patel et al., 2008; Tanaka and Uetake, 2005; Vuillerme and Pinsault, 2007). Thus, it can be suggested that the foam surfaces induced similar disturbances to the feet cutaneous receptors in the three ankle positions.

The subjects in the current study were required to maintain their gaze on a fixed marker which by itself is a cognitive task (Bonnet and Szaffarczyk, 2017; Bonnet, 2019). As such, a need to perform an additional cognitive task could potentially affect the COP measures. However, we believe this was not the case because the subjects were required to focus on the target in all the experimental conditions.

The study participants had no experience in standing over the inclined surfaces demonstrating increased body sway in such challenging conditions as compared to the natural stance. As such it is quite possible that a repetitive exposure to such challenge might improve their overall balance ability. The suggestion is supported by a recent literature: training involving standing and walking over unstable platforms or wearing unstable shoes could enhance balance control (Anderson and Behm, 2005) (Nigg et al., 2012). In particular, wearing unstable shoes is considered a proprioceptive training because such shoes induce postural instability and stimulate the inactive muscles around the ankle joints (Nigg et al., 2012). Consequentially, the experience in wearing unstable shoes can develop a more resilient control system that has a better adaption capability to the challenging environments (Buchecker et al., 2018).

It is also known that standing and walking over inclined surfaces (which is common in the construction industry where high incidents of falls occur), might compromise the stepping strategy that is often adopted to recover from a postural perturbation (Nadhim et al., 2016) (Pijnappels et al., 2010). While our study allowed obtaining data related to standing on inclined surfaces, future studies using the virtual reality paradigm that simulate an actual work condition could be beneficial to analyze the risk associated with standing with altered ankle joint positions (Eikema et al., 2013; Lubetzky et al., 2019).

The interpretation of the findings should be done in light of some limitations. First, we enrolled only young subjects with no prior experience in standing on a wedge inducing ankle plantarflexion or dorsiflexion. Second, the subjects were asked to maintain a quiet erect posture, while the natural human standing is a less strain posture with a greater level of asymmetry (Prado-Rico and Duarte, 2019). Third, given that the effects of the ankle angular position and standing surface type on static upright balance was studied over a short period of time, no conclusion about the role of inclined or soft surfaces in postural control during prolonged standing could be made.

Conclusions

An upright stance with dorsiflexed ankles appeared to be the least steady condition of static balance when compared to standing in a natural stance or with plantarflexed ankles. Standing on the surface covered with foam increased the postural instability. These findings provide a background for further exploration of the effects of ankle joint positions and surface types on postural control.

Figure legends.

Fig.1. Schematic representation of the experimental setup. Subjects were asked to maintain vertical stance while standing on a flat rigid surface (H), on a wedge that induced dorsiflexion (D) or plantarflexion (P) and while standing on each of the surfaces covered with foam.

Fig.2 COP velocity (mm/s) and distance (mm) in the anterior posterior (AP) and mediolateral (ML) directions for the three-ankle joint angular positions: natural stance (H); dorsiflexed ankle (D); plantarflexed ankle (P), averaged over the two surfaces types. Mean ± SE are shown. (*) (**) indicate significant difference between conditions at $p<.05$ and $p<.01$ respectively.

Fig.3 COP velocity (mm/s) and distance (mm) in the anterior posterior (AP) and mediolateral (ML) directions while standing on the firm (F) and soft (S) surfaces, averaged over the three ankle positions. Mean ± SE are shown. (**) indicate significant difference between surfaces at $p<.01$.

Figure 1

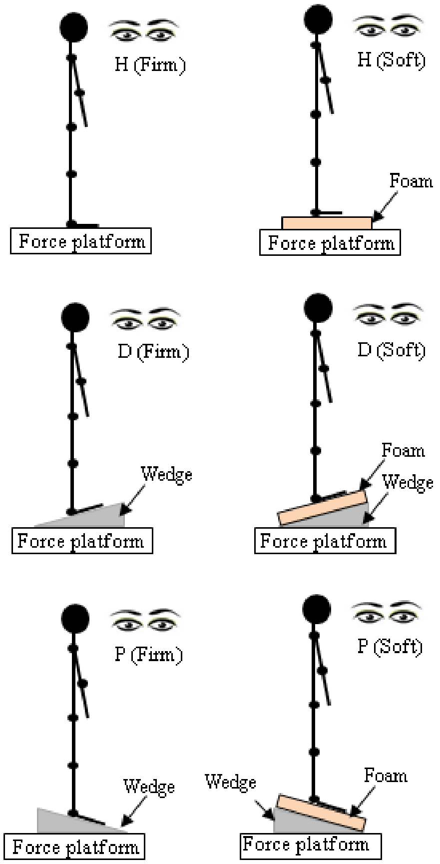


Figure 2

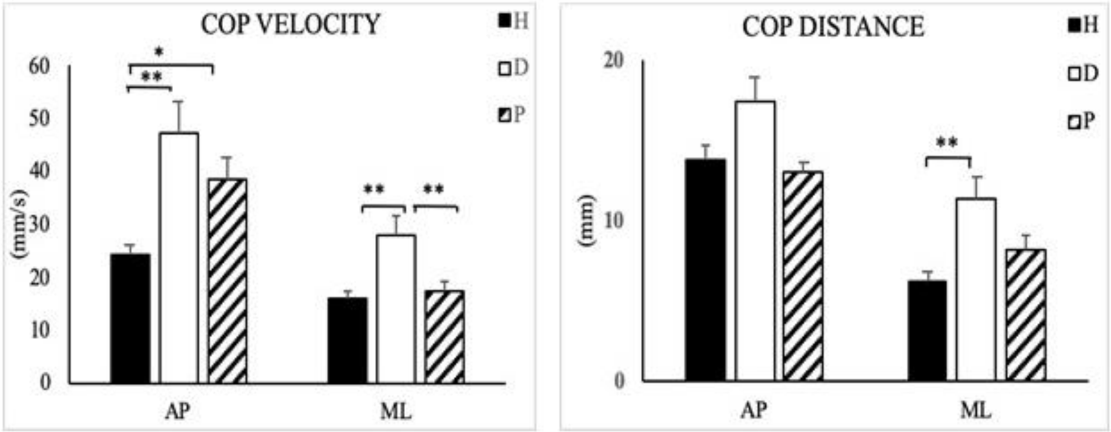
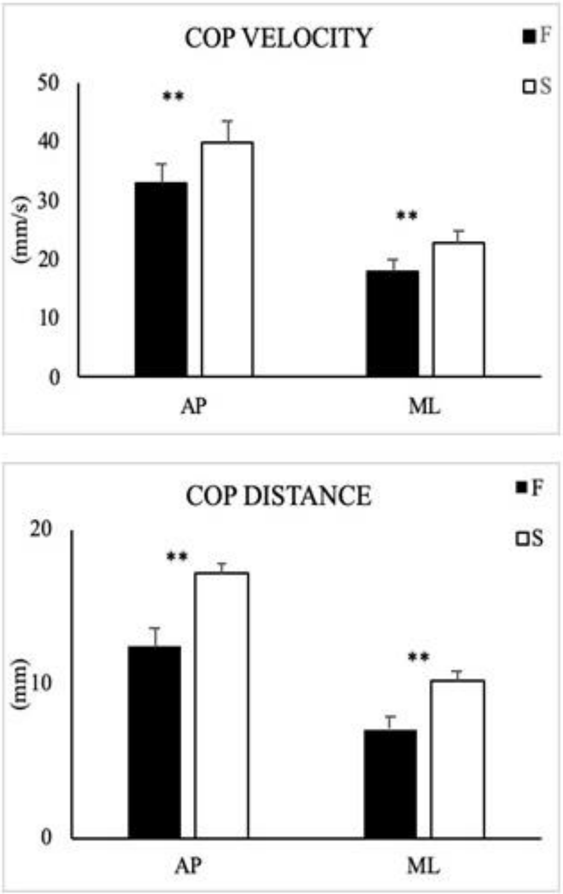


Figure 3


COP VELOCITY
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**
AP
ML
COP DISTANCE
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AP
ML

References

Anderson, K., Behm, D.G., 2005. The Impact of Instability Resistance Training on Balance and Stability. Sports Medicine. 35**,** 43-53.

Bonnet, C.T., Szaffarczyk, S., 2017. The Stationary-Gaze Task Should Not Be Systematically Used as the Control Task in Studies of Postural Control. Journal of Motor Behavior. 49**,** 494-504.

Bonnet, C.T., 2019. Positive Relations Between Vision and Posture in the Fixation Task Performed Upright. Motor control. 1-16.

Buchecker, M., et al., 2018. Unstable footwear affects magnitude and structure of variability in postural control. Motor control. 22**,** 1-17.

Bureau of Labor, S., 2016. Fatal Occupational Injuries by Industry and Event or Exposure, All United States, 2014.

Chiang, J.-H., Wu, G., 1997. The influence of foam surfaces on biomechanical variables contributing to postural control. Gait & Posture. 5**,** 239-245.

da Costa Barbosa, R., Vieira, M.F., 2017. Postural Control of Elderly Adults on Inclined Surfaces. Annals of Biomedical Engineering. 45**,** 726-738.

Di Giulio, I., et al., 2009. The proprioceptive and agonist roles of gastrocnemius, soleus and tibialis anterior muscles in maintaining human upright posture. The Journal of physiology. 587**,** 2399-2416.

Eikema, D.J.A., et al., 2013. Elderly adults delay proprioceptive reweighting during the anticipation of collision avoidance when standing. Neuroscience. 234**,** 22-30.

Freitas, S.M.S.F., Prado, J.M., Duarte, M., 2005. The use of a safety harness does not affect body sway during quiet standing. Clinical Biomechanics. 20**,** 336-339.

Ganesan, M., Lee, Y.-J., Aruin, A.S., 2014. The effect of lateral or medial wedges on control of postural sway in standing. Gait & Posture. 39**,** 899-903.

Garkavenko, V.V., et al., 2012. Modifications of the stabilogram during upright standing posture under conditions of inclines of the support surface. Neurophysiology. 44**,** 131-137.

Gefen, A., et al., 2002. Analysis of muscular fatigue and foot stability during high-heeled gait. Gait Posture. 15**,** 56-63.

Gerber, S.B., et al., 2012. Interference of high-heeled shoes in static balance among young women. Human Movement Science. 31**,** 1247-52.

Isableu, B., Vuillerme, N., 2006. Differential integration of kinaesthetic signals to postural control. Experimental Brain Research. 174**,** 763-768.

Ivanenko, Y., Gurfinkel, V.S., 2018. Human Postural Control. Frontiers in Neuroscience. 12**,** 171.

Kistemaker, D.A., et al., 2012. Control of position and movement is simplified by combined muscle spindle and Golgi tendon organ feedback. Journal of Neurophysiology. 109**,** 1126-1139.

Le Huec, J.C., et al., 2011. Equilibrium of the human body and the gravity line: the basics. European spine journal : official publication of the European Spine Society, the European Spinal Deformity Society, and the European Section of the Cervical Spine Research Society. 20 Suppl 5**,** 558-563.

Lee, Y.J., et al., 2017. Standing on wedges modifies side-specific postural control in the presence of lateral external perturbations. Journal of Electromyography and Kinesiology. 36**,** 16-24.

Li, L., et al., 2002. The function of gastrocnemius as a knee flexor at selected knee and ankle angles. Journal of Electromyography and Kinesiology. 12**,** 385-390.

Lin, D., Nussbaum, M.A., 2012. Effects of lumbar extensor fatigue and surface inclination on postural control during quiet stance. Applied Ergonomics. 43**,** 1008-1015.

Loram, I.D., Maganaris, C.N., Lakie, M., 2005. Active, non-spring-like muscle movements in human postural sway: how might paradoxical changes in muscle length be produced? The Journal of physiology. 564**,** 281-293.

Lubetzky, A.V., et al., 2019. An Oculus Rift Assessment of Dynamic Balance by Head Mobility in a Virtual Park Scene: A Pilot Study. Motor Control. 23, 127-142.

Maitre, J., Paillard, T.P., 2016. Influence of the Plantar Cutaneous Information in Postural Regulation Depending on the Age and the Physical Activity Status. Frontiers in human neuroscience. 10, 409-409.

Marieb, E.N., Tonini, C., Martin, T., 1998. Human anatomy & physiology, Vol., Benjamin Cummings, Menlo Park, Calif.; Harlow.

Massion, J., 1994. Postural control system. Current Opinion in Neurobiology. 4, 877-887.

Mezzarane, R.A., Kohn, A.F., 2007. Control of upright stance over inclined surfaces. Experimental Brain Research. 180, 377-88.

Mika, A., et al., 2016. The influence of high- and low-heeled shoes on balance in young women. Acta of Bioengineering & Biomechanics. 18, 97-103.

Nadhim, E.A., et al., 2016. Falls from Height in the Construction Industry: A Critical Review of the Scientific Literature. International journal of environmental research and public health. 13, 638.

Nigg, B., et al., 2012. Unstable shoes: functional concepts and scientific evidence. Footwear Science. 4, 73-82.

Patel, M., et al., 2008. The effect of foam surface properties on postural stability assessment while standing. Gait & posture. 28, 649-656.

Pijnappels, M., et al., 2010. The association between choice stepping reaction time and falls in older adults—a path analysis model. Age and ageing. 39, 99-104.

Prado-Rico, J.M., Duarte, M., 2019. Asymmetry of Body Weight Distribution During Quiet and Relaxed Standing Tasks. motor control.

Prieto, T.E., et al., 1996. Measures of postural steadiness: differences between healthy young and elderly adults. IEEE Transactions on biomedical engineering. 43, 956-966.

Proske, U., 2006. Kinesthesia: the role of muscle receptors. Muscle Nerve. 34, 545-58.

Roaas, A., Andersson, G.B.J., 1982. Normal Range of Motion of the Hip, Knee and Ankle Joints in Male Subjects, 30–40 Years of Age. Acta Orthopaedica Scandinavica. 53, 205-208.

Shumway-Cook, A., & Woollacott, M. H., 2012. Motor control: Translating research into clinical practice, Vol., Wolters Kluwer Health/Lippincott Williams & Wilkins., Philadelphia.

Soucie, J.M., et al., 2011. Range of motion measurements: reference values and a database for comparison studies. Haemophilia. 17, 500-7.

Tanaka, H., Uetake, T., 2005. Characteristics of postural sway in older adults standing on a soft surface. Journal of Human Ergology. 34, 35-40.

Vuillerme, N., Pinsault, N., 2007. Re-weighting of somatosensory inputs from the foot and the ankle for controlling posture during quiet standing following trunk extensor muscles fatigue. Experimental Brain Research. 183, 323-327.

Winter, D.A., et al., 1998. Stiffness Control of Balance in Quiet Standing. Journal of Neurophysiology. 80, 1211-1221.