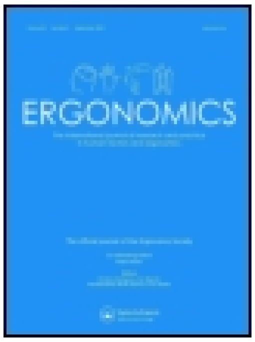

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Footwear effects on walking balance at elevation

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The study evaluated the effects of shoe style on workers' instability during walking at elevation. Twenty-four construction workers performed walking tasks on roof planks in a surround-screen virtual reality system, which simulated a residential roof environment. Three common athletic and three work shoe styles were tested on wide, narrow and tilted planks on a simulated roof and on an unrestricted surface at simulated ground. Dependent variables included lateral angular velocities of the trunk and the rear foot, as well as the workers' rated perceptions of instability. The results demonstrated that shoe style significantly affected workers walking instability at elevated work environments. The results highlighted two major shoe-design pathways for improving walking balance at elevation: enhancing rear foot motion control; and improving ankle proprioception. This study also outlined some of the challenges in optimal shoe selection and specific shoe-design needs for improved walking stability during roof work. The study adds to the knowledge in the area of balance control, by emphasising the role of footwear as a critical human–support surface interface during work on narrow surfaces at height. The results can be used for footwear selection and improvements to reduce risk of falls from elevation.

Keywords: virtual reality; height; walking balance; footwear; construction; roof

1. Introduction

Falls from elevation remain the leading cause of fatal injury in the US construction industry. According to the Bureau of Labor Statistics, in 2006, approximately 424 construction workers lost their lives and 18,230 were seriously injured in falls from elevation (Bureau of Labor Statistics 2007a,b). Loss of balance was identified as one of the triggering events in fall-from-roof incidents during construction work (Parsons and Pizatella 1985, Hsiao and Simeonov 2001). The control of balance is maintained through integration of sensory information from the visual, vestibular and somatosensory systems (Tinetti and Speechley 1989). Workers in roof construction perform a variety of tasks for extended periods of time on elevated and narrow, compliant and inclined work surfaces. These conditions may adversely affect workers' balance control systems and increase their risk of falling (Choi and Fredericks 2008). Earlier research suggested that exposure to elevation can induce instability (Lee and Lishman 1975) and lead to height vertigo (Bles *et al*. 1980). Recently, it was demonstrated that exposure to elevation significantly

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increased workers' postural sway parameters and this effect was especially pronounced on deformable and sloped support surfaces (Simeonov and Hsiao 2001, Simeonov *et al.* 2003). Furthermore, due to the reduced visual control of balance at elevated environments, the workers' postural control systems rely heavily on proprioceptive inputs, i.e. somatosensory information from receptors in the plantar surface and the muscles and joints in the feet (Simeonov and Hsiao 2001, Simeonov, *et al.* 2003).

Shoes act as a sensory interface between the foot and the surface of support; thus, a modification in the characteristics of this interface may affect postural stability (Menz and Lord 1999, McPoil 2000). Sensory inputs play a dominant role in the maintenance of the dynamic stability during walking activity (Patla 2003). Reduction of sensory information has a greater impact on lateral stability and less effect on fore–aft stability during gait (Bauby and Kuo 2000). Therefore, it is likely that the unreliable visual inputs at elevation and the modified somatosensory information from footwear will affect predominantly workers' lateral stability.

Lateral stability during walking on unrestricted surfaces is most efficiently controlled by the 'mediolateral foot placement' (MacKinnon and Winter 1993, Bauby and Kuo 2000, Patla 2003). On narrow walking surfaces (e.g. 15 cm), which enforce suboptimal step width (Donelan *et al.* 2001), the 'mediolateral foot placement' strategy is not available and the only remaining effective way to control balance in the frontal plane is the individual or combined use of 'ankle' and 'hip' strategies, i.e. the lateral tilting movements at the foot and the trunk. It has been proposed that shoe properties can modify the effectiveness of the foot-tilt control activity and that proper footwear may improve lateral balance in the elderly (Hoogvliet *et al.* 1997). In that order, some sport shoe design features have been shown to strongly influence the medial–lateral stability of the foot and thus affect the incidence of injury and performance (Frederick 1986), as well as postural balance (Robbins *et al.* 1994).

In the last decade the footwear industry has made considerable progress in improving the properties of athletic footwear, which has resulted in the design of numerous types and styles of athletic shoes, e.g. walking, running and cross-training. This progress has also affected the safety footwear industry, which has introduced new shoe styles, i.e. athletic safety shoes, and improved both the comfort and performance of traditional work shoes and boots by using new cushioning technologies and safety devices. Both work and athletic shoe styles are used by construction workers. Since the requirements for a shoe design are controversial, there is no universal or 'perfect' shoe for all tasks and the use of different shoe styles is associated with various advantages and disadvantages. There is a lack of knowledge of the effects of footwear on balance performance at elevated construction environments.

The current footwear requirements for the construction industry address mainly the need for foot protection, e.g. from impact or puncture, and does not invoke issues related to balance and fall prevention associated with footwear (Occupational Safety and Health Administration 1993). Occupational Safety and Health Administration standards provide only broad recommendations for the use of footwear on roofs: 'The employer shall have workers wear appropriate footwear to reduce the potential for slipping' (Occupational Safety and Health Administration 1999). In addition, a recent standards interpretation indicates that there are no requirements regarding any specific type of footwear (athletic or work) for work on a roof (due to the large variability in footwear properties and roof surface conditions) (Occupational Safety and Health Administration 2004). On most non-industrial job sites, small contractors, carpenters and roofers are responsible for selecting their own footwear. Field observations, as well as industry-related sources, demonstrate that during work at heights, i.e. roof construction, workers frequently use a variety of footwear types and many prefer to wear various athletic shoes (Greenlaw 2000). There is a lack of information to develop recommendations for shoe selection for such dangerous activities as construction work on roofs. Currently, workers select shoes mostly based on individual experiences, perceptions and preferences. Further, factors such as fashion and appearance play an important role in shoe selection (Falcinelli 2001). There is a need to determine the most appropriate shoe styles for improved balance control during work at elevated construction sites. Such information may help to develop recommendations for shoe selection and to improve the shoe design for such activities.

This study filled the above-mentioned gap by investigating footwear style effects on workers' walking balance in a challenging construction environment. The overall study hypothesis was that shoe design can significantly affect workers' lateral stability during walking on narrow and tilted planks in roof environments.

2. Method

2.1. *Participants*

A sample of 24 male construction workers, experienced with working at height, participated in the study. They were recruited from the local Morgantown, WV area. They had an average age of 39 (range 23–53) years, average height of 178.3 (SD 6.9) cm and average weight of 86.4 (SD 12.6) kg. The requirements for study participation were: normal or corrected vision in both eyes; free of known balance problems; not fearful of heights; no medication use and alcohol consumption in the last 24 h; 18 years of age or older. All participants gave informed consent prior to the study and were compensated for their time. The experimental protocol was approved by the Human Subjects Review Board of the National Institute for Occupational Safety and Health.

2.2. *Experimental procedure*

The participants were briefed on the study objectives, methods, procedures and potential risks. They were allowed time to experience the virtual environment and given the opportunity to get acquainted with the tasks and the test procedures. The participants then changed into tightly fitting clothes and socks, provided by the laboratory, to allow the accurate measurement of body movement by the attached markers. The experimental session included 24 experimental conditions. Each task was repeated three times at each experimental condition. All tests were conducted in a surround screen virtual reality (SSVR) system. The participants were asked to walk with self-preferred speed in six different shoe styles in four environmental conditions. The participants were also instructed to walk straight on the narrow boards, i.e. to maintain a normal gait pattern while facing the direction of walking and keeping their feet aligned to the board axis as much as possible. The participants completed each 3-m walking distance in two to three strides (four to six steps). The experimental conditions included level and tilted (at 14° angle) 25-cm-wide planks and a level 15-cm-wide plank positioned on the floor (i.e. the lower screen) of the SSVR system, while it visually simulated a residential roof environment. A fourth experimental condition involved walking on a laterally unrestricted surface – the floor (i.e. the lower screen) of the SSVR, while it visually simulated the ground level of the same construction site. The test order was balanced (i.e. each treatment was preceded equally as often by every other treatment) to average out the variance associated with possible learning and fatigue effects. There was a 2-min rest interval between experimental conditions and a 5-min break between each shoe-style condition. The participants completed the test session in approximately 2 h and were compensated for their time. Before the start and at the end of the experimental session the participants completed two balance performance tests (National Highway Traffic Safety Administration 2000) to ensure that the virtual environment exposure had no adverse effects. All participants successfully passed the balance performance tests.

2.3. *Experimental design and independent variables*

The study used a balanced repeated measures design with two compound independent variables – footwear and environment. The footwear variable had six levels and consisted of athletic and work shoe type groups with three shoe styles in each group. The environment variable had four levels and allowed the evaluation of walking surface width and walking surface lateral slope (tilt) effects in a simulated roof workplace.

2.3.1. *Footwear variable (six shoe styles)*

Samples of the test shoe styles were tested for their mechanical properties at the Biomechanics Laboratory, Department of Exercise Science, University of Massachusetts, Amherst, MA, USA. An Exeter Research Impact Tester (Exeter Research, Brentwood, NH, USA) was used to assess the impact attenuation properties of the shoe with two measures – peak acceleration, for which a lower number indicates a greater shock attenuation, and time-to-peak acceleration, for which a higher number indicates a greater shock attenuation. This instrument is designed to test footwear according to proposed, but not yet adopted, American Society for Testing and Materials (ASTM) standards. The flexibility test was carried out on a specially designed flexion machine, modelled after the one used by Cavanagh (1980) – a lower number of the measure flex stiffness indicates less stiff forefoot. An Exeter Research Torsion Tester (Exeter Research) was used to assess the resistance to torsion in the midfoot of the footwear – a higher number of the measure torsion indicates higher resistance to torsion. The test results are summarised in Table 1.

The three athletic shoe styles included a running shoe, a tennis (court) shoe and a basketball shoe (see Figure 1a). These shoes selected for testing represent the mid-price

Table 1. Footwear properties.

	Athletic shoe styles			Work shoe styles		
	Running	Tennis	Basketball	Work low-cut	Work boot	Safety boot
Impact-PG, G	8.43	8.59	8.79	8.76	10.05	11.91
Impact-TTP (ms)	14.20	12.60	11.20	10.10	9.27	9.43
Initial flex stiffness* (Nm/deg)	0.17	0.35	0.35	0.42	0.47	0.54
Torsion† (Nm)	3.80	5.34	5.70	7.22	7.16	7.59
Width at heel (cm)	8.5	9.1	9.2	8.7	8.7	8.7
Weight (g)	312	416	472	642	690	768

Note: All the tested shoe samples were men's US size 9 (European size 42.5, British size 8.5).
PG = peak acceleration (low numbers indicate greater shock attenuation).
TTP = time to peak acceleration (higher numbers indicate greater shock attenuation).
*Lower numbers indicate less stiff forefoot.
†Higher numbers indicate greater resistance to torsion.
G = gravity unit for acceleration.

Figure 1. Test shoes. a) Athletic shoe styles; from left to right: running shoe; tennis shoe; basketball shoe; b) work shoe styles; from left to right: low-cut work shoe; work boot; safety boot.

range shoes of a commercially available brand. They did not include the latest technological developments (e.g. absorption/suspension systems and stability webs and wedges) that are currently advertised by the industry. The running shoe style was designed for good impact absorption (shock attenuation) and minimal resistance to the movement of the foot. It is characterised with low weight, low flex stiffness and low torsional resistance (see Table 1). The tennis shoe style was designed for both good impact absorption and superior motion control characteristics. This shoe had higher flex stiffness and torsional resistance than the running shoe. The basketball shoe was designed for good impact absorption and good lateral support with additional ankle support provided by the higher upper. A comparison between the tennis and the basketball shoes reflects the effect of the shoe upper, since the two shoes are similar in most of the other characteristics.

The three work shoe styles were all of one brand series and included a work shoe (low-cut, no toe protection), 15-cm work boot (no toe protection) and a 15-cm safety boot with steel toe protection (see Figure 1b). They were selected as medium-price range shoes with very good quality and wide availability. The work shoes were characterised with higher stiffness, both in flex and torsion as compared to the athletic shoes (see Table 1). The shoe soles and the shoes as a whole were relatively flexible, felt comfortable immediately and did not require extensive time for 'breaking in the new shoe'. The outer sole of the work shoes provided a good grip and was rated by the manufacturer as 'slip resistant'. In addition, the shoe sole had an integrated steel shank support. A comparison between the low work shoe and the work boot revealed the effect of the shoe upper. A comparison between the work boot and the safety boot reflected the effect of the steel toe protection and the overall higher stiffness of the safety shoe.

In addition, to determine the overall effect of the design characteristic 'shoe upper', the shoes were grouped into a 'high-cut' group, including the two boot-style work shoes and the basketball shoe, and a 'low-cut' group, including the running shoe, the tennis shoe and the low-cut work shoe.

2.3.2. *Environment variable (four experimental conditions)*

The environment variable included the following four experimental conditions: a virtual roof with two level planks (of different width) and one tilted plank, plus simulated ground with a laterally unrestricted flat surface, which served as a baseline. The experimental conditions were created in the SSVR system using a virtual roof model, augmented with real wood planks. The visual environment was a computer-generated simulation of the sloped roof with pitch angle 22° of a three-storey building, in the locale of a residential neighbourhood (see Figure 2). The participants had the impression of being at height, while walking on roof planks, in close proximity to the roof edge. In reality, they performed the walking tasks on planks positioned on the floor of the SSVR system, while the system projected computer-generated interactive stereo images on the floor screen and on the three surrounding screens (see Figure 3). The simulated height environment could induce equivalent postural instability effects and mild anxiety levels as compared to a real height environment (Simeonov *et al*. 2005). Real wood planks (3 m long and 4.5 cm thick), instead of virtual planks, were used as walking surfaces, as they could provide more realistic testing conditions (Hsiao *et al*. 2005). To reduce possible distracting and destabilising effects of a mismatch between the virtual plank image and the real plank, the image was adjusted to cover the plank surface completely, so that the plank edges remained clearly visible and provided a stable reference for the participants. The four environmental conditions allowed discrete evaluation of the effects of plank-surface width and plank-surface slope on all dependent variables.

2.3.3. *Plank surface width*

Two levels of walking surface width (25-cm and 15-cm wide planks) were used to test the effects of footwear and its interaction with walking surface width on walking stability.

Figure 2. The virtual roof environment with a participant on the roof plank.

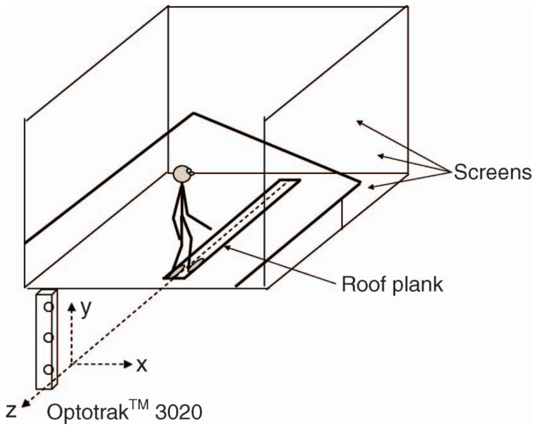


Figure 3. Schematic diagram of the experimental setup in the surround screen virtual reality system.

The 25-cm wide plank represents a roof plank, commonly used in the residential roof construction practice as a support and walking surface attached to the roof by roof jacks. The 15-cm wide plank represents a narrow walking surface. This extreme condition is frequently encountered by the workers at a construction site. It is used especially in steep-roof construction, as a roof plank, or when the top of a wall ('top plate') is used as a support and walking surface to move from one area to another in the construction process – e.g. during truss installation. To provide realistic mechanical response, the planks were supported at both ends and in the middle by 4.5×9.0 cm wood blocks. The deflection of the planks from a 78 kg person standing at mid-span was 13 mm for the 15 cm plank and 7 mm for the 25 cm plank. Walking on a laterally unrestricted flat surface – the visually simulated ground level on the floor of the SSVR system – was used as a baseline.

2.3.4. Plank surface slope (tilt)

Two levels of plank lateral slope were evaluated – level surface (0° slope) and sloped surface (14° slope). The plank slope (tilt) variable was only applied to the width of the 25-cm plank, i.e. in lateral direction to the direction of movement. In roofing practice, the planks are frequently positioned at an angle to serve as a slide guard as well as a support and walking surface. Walking along the tilted board creates an additional challenge to gait stability in the medial–lateral direction. The plank slope (tilt) of 14° was selected based on observations of roofing practices.

2.4. Dependent variables

2.4.1. Parameters for assessing the trunk angular displacement in the frontal plane

The angular displacement of the upper body (trunk) in the frontal plane was calculated from the displacements of one sacral marker and one thoracic marker (T3). For the calculations, the first and the last 60 cm of the walking path were excluded to eliminate the gait initiation and termination phases. The angular movement of the upper body reflects a 'hip strategy' of lateral balance control during walking (MacKinnon and Winter 1993), known also as a 'trunk-tilt' strategy. An increased trunk angular motion, i.e. lateral angular velocity, may indicate instability and is considered a good predictor of falling tendency among the elderly (Allum and Carpenter 2005). The initial analyses included four variables: standard deviation; range; mean velocity; maximum velocity of the trunk angular displacement.

2.4.2. Parameters for assessing the rear foot angular displacement in the frontal plane

The angular displacement of the rear foot in the frontal plane was calculated from the displacements of markers attached to the rear foot and the lower leg, according to a method for measuring rear foot motion during walking (Cornwall and McPoil 1993) and a modified standard procedure for testing rear foot motion-control properties of running shoes (American Society for Testing and Materials 1997). The angular motion variables were determined only from the portion of the stance phase, in which the horizontal (anterior–posterior) and vertical components of the rear foot/shoe movement approached zero, i.e. the 'standing foot phase', when the shoe sole was in complete contact with the support surface. The angular motion parameters were calculated as averages from the movement of both the left and the right foot/shoe during several consecutive steps (four to six values). Initial calculations and evaluation included the variables standard deviation, range, mean velocity and maximum velocity of the absolute rear foot angular displacement and the rear foot angular displacement relative to the lower leg (American Society for Testing and Materials 1997).

The 'rear foot angular motion' in the frontal plane can serve as an indirect measure of whole body mediolateral stability under certain conditions. For example, it may reflect the intensity of the lateral balance control activity at the lower ankle (subtalar) joint (i.e. a 'foot tilt' strategy) during the single support phase in walking (MacKinnon and Winter 1993). The 'foot tilt' strategy is actively involved in the control of walking balance on laterally restricted surfaces; therefore, the 'rear foot angular motion' may be a useful measure to compare effects of walking surface width under the same shoe conditions. Since the 'rear foot angular motion' is measured from markers attached to the rear shoe, it also reflects the mechanical behaviour of the shoe in response to the loading from the 'tilt' movements of the foot, i.e. it is also a relative measure of the shoe motion control properties (American Society for Testing and Materials 1997) and can be useful for comparison of shoe lateral stability properties under similar walking environment conditions. Thus, the 'rear foot angular motion' variable synergistically reflects both the whole body lateral instability and the shoe lateral instability.

2.4.3. Perception of instability

A short questionnaire (Chiou *et al.* 1998) was used to determine the participants' perceptions of instability during the walking tasks. This questionnaire consisted of four simple questions that the participants answered after each test: 'How much did you feel your body sway?', 'Did you have any difficulty in maintaining balance?', 'Did you feel at any time that you would fall?' and 'What was the overall difficulty of this task?', The participants used a visual analogue scale to rate their perceptions in the range 0–10 ('not at all' – 'a lot'). The perceived instability (PI) was calculated as the sum of the four answers.

2.4.4. Perceived shoe comfort

The rated perceptions of shoe comfort were assessed using a visual analogue scale method (Mundermann *et al.* 2001). The participants rated their perceptions in the range 0–10 ('not comfortable' – 'most comfortable'). The shoe comfort measure was the average of three ratings given throughout the testing process. Time was allowed to the participants in the beginning of each test session with a new pair of shoes to get the initial 'feel of shoe comfort'. During this time period the participants were encouraged to perform movements that they normally use in selecting a new pair of shoes in a footwear store.

2.5. Equipment

2.5.1. Virtual reality system

A SSVR system was used to simulate the elevated roof construction environment. The projection-based SSVR system had three 3.6 m $\times$ 3.0 m walls and a 3.6 m $\times$ 3.6 m floor (see Figure 3). Four PCs controlled the projected images at a resolution of 1024 $\times$ 768 and a 96 Hz stereo signal, for a 48 Hz effective scene refresh rate. The liquid crystal shutter glasses (Crystal Eyes-2; StereoGraphics Inc., San Rafael, CA, USA) allowed a participant's field of view of approximately 100° in the horizontal and 50° in the vertical direction. The average time delay of the system was approximately 55 ms (Simeonov *et al.* 2005).

2.5.2. Kinematic measurement system

The angular motion of the rear foot and the torso in the frontal plane was collected using an Optotrak (model 3020) motion measurement system (Northern Digital Inc., Waterloo, Ontario, Canada). In total, 14 markers were attached to the participant's body: one at the sacrum, one at the third thoracic vertebra (T3), three on each lower leg and three on each rear foot. The rear foot angular motion was determined following a modification of the protocol described in ASTM standard for comparison of the motion control properties of running shoes (American Society for Testing and Materials 1997). To avoid the occlusion of the markers by the trailing leg during walking on the narrow planks, the markers were positioned on rigid aluminium fixtures (brackets), attached to the shoe with small bolts and to the lower leg with Velcro® stripes (see Figure 4). The data collection frequency was 100 Hz. Data processing and calculation of all motion variables were done with custom written programmes (macros) using Visual Basic in Microsoft Excel (Microsoft Corporation, Richmond, WA, USA). Fourth order polynomial algorithm was used to interpolate missing data points. Portions with more than 15 missing data points were not considered in the analysis.

2.6. Statistical analysis

Multivariate ANOVA (MANOVA) was used to evaluate the overall effects of shoe style and environmental condition on all instability measures of 13 dependent variables (four for the trunk angular motion, eight for the foot angular motion and one for instability perceptions). Follow-up analyses were performed to assess the key dependent variables after significant multivariate analysis. Dependent variable contributions were assessed using the standardised coefficients and the associated eigenvalues in the successive MANOVA by eliminating one at a time. A stepwise approach was used to determine a

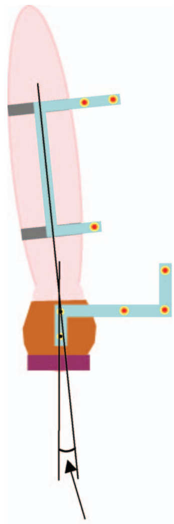


Figure 4. Schematic diagram of the rear foot marker set-up.

subset of dependent variables that had both practical use and statistical significance. The changes in the multivariate F values were also examined and used as additional information in the variable selection process.

Subsequent univariate ANOVA with repeated measures were performed and the three dependent variables, representing the trunk mean angular velocity, the absolute mean rear foot angular velocity and the PI, were used to interpret the results. For each dependent variable, several models were tested, first to find the appropriate covariance structure of observations within a participant. They were: (1) direct product compound-symmetry; (2) direct product unstructured; (3) direct product autoregressive. The model that provided the best fit based on Akaike's Information Criterion (AIC), a modified criterion from AIC for use in small samples (AICC) and Schwarz's Bayesian criterion was selected to be included in the final analysis.

Contrast analyses and multiple comparison tests were performed for specific hypothesis testing related to shoe properties and selected environmental conditions. Bonferroni adjustment was used in these analyses to determine the significance of the least square means differences among experimental conditions for the *p*-values.

Finally, to evaluate the association among the three dependent variables, an intra-class correlation coefficient from the repeated measure ANOVA was calculated over the range of the experimental conditions. All analyses were performed using Statistical Analysis System software (SAS Institute Inc., Cary, NC, USA).

3. Results

3.1. *Results of multivariate analysis of variance*

The initial MANOVA with 13 dependent variables considered simultaneously showed significant main effects for environment (Wilks' Lambda with $F_{39,\ 169.54} = 9.12$, $p < 0.0001$), footwear ($F_{65,\ 490.7} = 3.39$, $p < 0.0001$) and the interaction of footwear and environment ($F_{195,\ 3319.2} = 1.66$, $p < 0.0001$). A subset consisting of three key dependent variables – trunk mean angular velocity (from hereon called 'trunk angular velocity' (T-AV)), absolute rear foot mean angular velocity (from hereon called 'rear foot angular velocity' (F-AV)) and PI, identified from successive MANOVA also showed significant main effects and interactions for environment and footwear ($p < 0.0001$ for all main and interaction effects using Wilks' Lambda statistic). Subsequent univariate analyses results of the three key dependent variables are described below.

3.2. Trunk angular velocity

A four $\times$ six (environment $\times$ footwear) ANOVA was performed on the variable T-AV. The analysis indicated significant effect of environment ($F_{3, 69} = 29.79$, $p < 0.0001$). Walking on narrow and sloped planks at simulated height caused greater T-AV as compared to the unrestricted surface at the simulated ground level. Overall, T-AV was highest on the 15-cm plank, followed by the 25-cm tilted plank and by the 25-cm horizontal plank. All comparisons were statistically significant ($p < 0.05$).

There was a significant two-way interaction for footwear and environment on T-AV ($F_{15, 345} = 1.89$, $p = 0.0229$). Workers had similar T-AV with different shoes while walking at the simulated ground level. On the roof planks, however, the shoe type affected workers' T-AV and the shoe type effects were stronger at the narrower plank. Overall, the 'high-cut' shoes resulted in significantly ($p < 0.05$) lower T-AV than the 'low-cut' shoes, both on the 15-cm and the 25-cm planks, but not on the tilted plank. On the 15-cm plank, T-AV was highest for the running shoes and lowest for the safety boots. Among the athletic shoes, T-AV for the tennis and the basketball shoes was significantly ($p < 0.05$) lower than for the running shoes (see Figure 5a).

Among the work shoes, T-AV was generally lower for the work and safety boots as compared to the work low-cut shoes; however, the differences did not reach statistical significance ($p > 0.05$). A contrast comparison demonstrated a significant interaction between the safety or the work boots and the work low-cut shoes for walking on the 25-cm horizontal plank vs. walking on the 15-cm plank ($p = 0.0516$ or $p = 0.0005$ respectively). During walking on the roof planks, workers' T-AVs were less affected by the reduced plank width when they were wearing safety or work boots as compared to work low-cut shoes (see Figure 5b).

Walking on the tilted 25-cm plank was associated with significantly ($p < 0.05$) greater T-AV as compared to the horizontal 25-cm plank. The interaction between shoe type and plank tilt for T-AV was not statistically significant ($p > 0.05$).

3.3. Rear foot angular velocity

A four $\times$ six (environment $\times$ footwear) ANOVA was performed on the variable F-AV. The analysis indicated significant main effects of environment ($F_{3, 69} = 147.51, p < 0.0001$) and footwear ($F_{5, 115} = 36.33, p < 0.0001$). Walking on narrow planks at simulated height caused higher F-AV as compared to the unrestricted surface at simulated ground level. Overall, in the walking tasks, the running shoes had the highest F-AV followed by the work boots and the work shoes, and the tennis shoes had the lowest F-AV.

There was a significant two-way interaction for footwear and environment on F-AV ($F_{15, 345} = 3.90, p < 0.0001$). Overall, the more challenging walking surfaces amplified the shoe style effects on F-AV. For walking on ground level with athletic shoes, the running shoes had greater F-AV than the tennis and the basketball shoes ($p < 0.05$); on the narrow roof planks these differences increased considerably ($p < 0.05$). Further, the

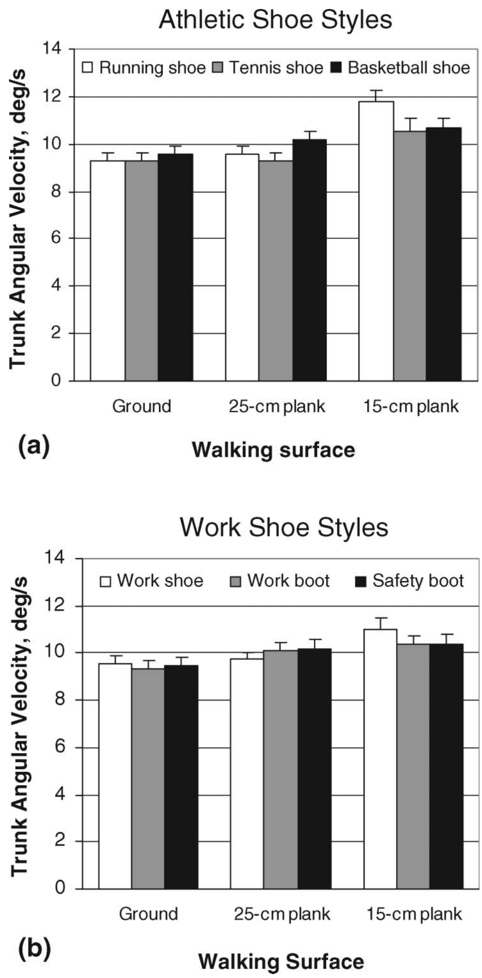


Figure 5. Trunk angular velocity – interaction of footwear style and plank width. a) Athletic shoe styles; b) work shoe styles.

tennis and the basketball shoes had similar F-AV on all horizontal walking surfaces (see Figure 6a). For walking at the ground level, the three work shoes styles had similar F-AV; however, on the roof planks, the safety boots had smaller ($p < 0.05$) F-AV than both the work shoes and the work boots (see Figure 6b). Overall, the 'high-cut' shoes resulted in significantly ($p < 0.05$) lower F-AV than the 'low-cut' shoes on the 15-cm plank but not on the 25-cm planks. Among all shoe types on the 15-cm plank, the running shoes had the highest F-AV and the safety boots together with the tennis and the basketball shoes had the lowest F-AV.

Walking on the tilted 25-cm plank was associated with significantly ($p < 0.05$) greater F-AV as compared to the horizontal 25-cm plank. Further, the lateral slope of the walking surface modified the effect of some shoe types on F-AV. Generally, the F-AV for the athletic shoes was similarly affected by the slope (see Figure 7a), while the F-AV for the work shoes reflected some differences in their response to slope. For example, among the work shoes, there was a significant ($p < 0.05$) interaction between work low-cut shoes

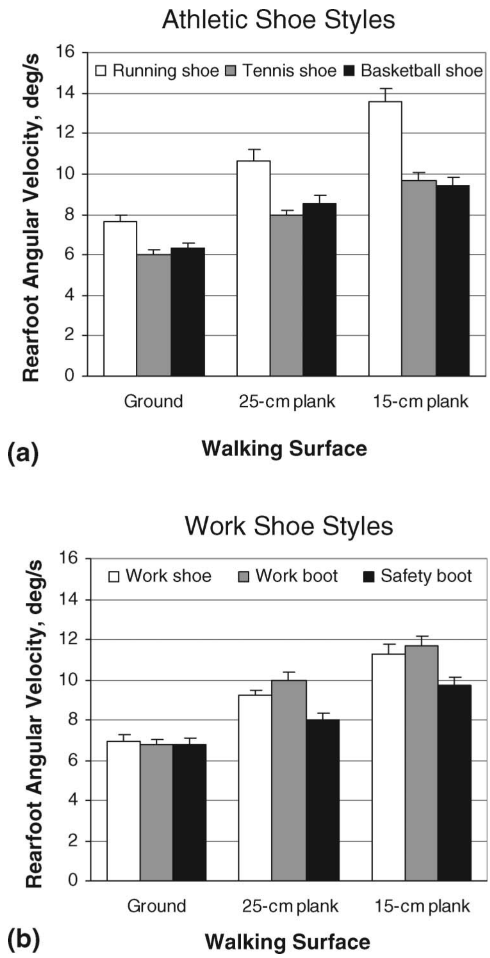


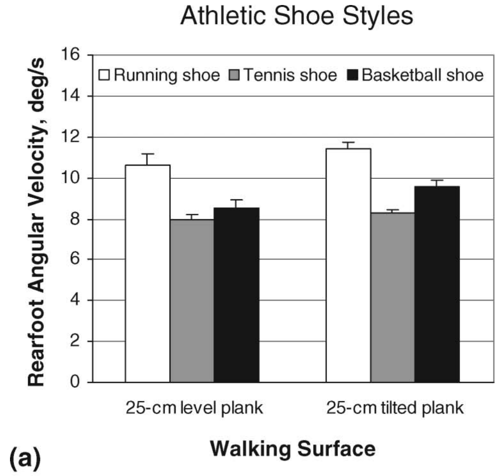
Figure 6. Rear foot angular velocity – interaction of footwear style and plank width. a) Athletic shoe styles; b) work shoe styles.

and safety boots for F-AV (see Figure 7b). Surface lateral slope caused less increase in F-AV for the work low-cut shoes as compared to the safety boots.

The average results for F-AV followed similar trends as the results for T-AV and the correlation analysis demonstrated a very good association between the two instability measures ($r = 0.7526$, $p = 0.0008$).

3.4. *Perceptions of instability*

A four × six (environment × footwear) ANOVA was performed on the variable PI. The analysis indicated significant effect of environment ($F_{3,\ 69} = 93.56$, $p < 0.0001$). Workers felt considerably more unstable on the narrow planks at simulated height as compared to the unrestricted surface at simulated ground level. Walking on the 15-cm plank was perceived as the most unstable condition, followed by the 25-cm tilted plank and the 25-cm horizontal plank.



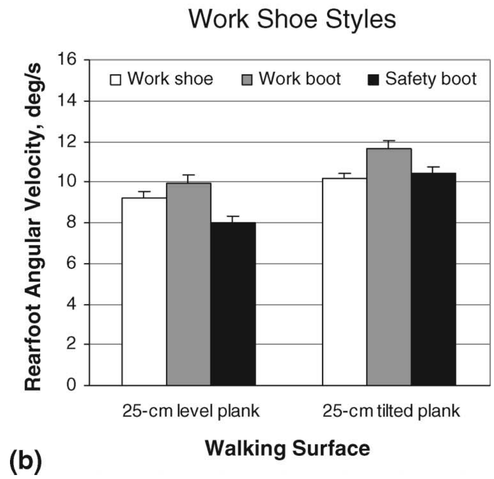


Figure 7. Rear foot angular velocity – interaction of footwear and plank tilt. a) Athletic shoe styles; b) work shoe styles.

The main effect of footwear also showed statistical significance ($F_{5,\ 115} = 2.85$, $p = 0.0184$), and there was a significant two-way interaction for footwear and environment ($F_{15,\ 345} = 1.72$, $p = 0.0451$). Workers had similar instability perceptions while walking with different shoes on the unrestricted surface at simulated ground level. On the roof planks, however, the shoe type affected workers' instability perceptions and the effects were stronger on the narrower plank.

Overall, workers felt significantly ($p < 0.05$) more stable in the 'high-cut' shoes as compared to 'low-cut' shoes on the 15-cm and the 25-cm planks, but not on the tilted plank. While walking on the 15-cm plank workers felt least stable in the running shoes and most stable in the work boots. Among the athletic shoes, workers felt significantly ($p < 0.05$) more stable with basketball and tennis shoes as compared to running shoes and among the work shoes they felt significantly ($p < 0.05$) more stable in work and safety boots as compared to low-cut work shoes (see Figure 8a,b).

Workers felt significantly ($p = 0.0007$) more unstable when walking on a tilted as compared to a horizontal 25-cm plank. Furthermore, the results indicated that the lateral slope of the walking surface modified the shoe effects observed on the horizontal planks. On the horizontal plank, workers felt more stable in basketball as compared to tennis shoes and this pattern was not statistically significant ($p > 0.05$) for the tilted plank condition.

The average results for PI had similar trends with both T-AV and F-AV. The correlation analyses demonstrated good overall association between the parameters for perceived and measured instability – r = 0.4446, $p = 0.0021$ for PI and T-AV and r = 03406, $p = 0.0017$ for PI and F-AV.

3.5. *Perception of comfort*

A one way (footwear × six) ANOVA was performed on the variable perceived comfort. The results did not show significant effects of shoe style on perceived comfort ($F_{5,114} = 1.66$,

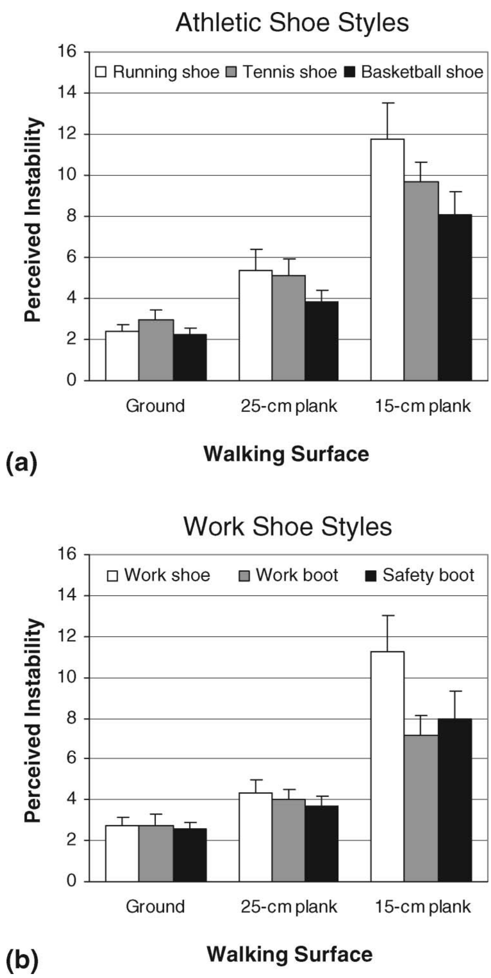


Figure 8. Perceptions of instability – interaction of footwear style and plank width. a) Athletic shoe styles; b) work shoe styles.

$p = 0.1490$). The differences in the comfort ratings were relatively small – the average comfort ratings for all shoes were in the narrow range 5.54–6.77, i.e. above the average comfort level. Among all shoes, basketball shoes received the highest comfort rating, followed by the running shoes, work boots, tennis shoes, safety boots and the low-cut work shoes.

4. Discussion

The study results supported the hypothesis that shoe style can significantly affect workers' lateral walking stability on narrow planks at elevated work environments simulated in a SSVR system. The study highlighted two major shoe-design pathways for improving walking balance at elevation – enhancing rear foot motion control and improving ankle motion proprioception. In addition, it outlined some of the challenges in optimal shoe design for improved lateral stability during walking on a tilted surface.

4.1. Trunk and rear foot kinematics

4.1.1. Surface width effects

The significant effect of surface width on T-AV demonstrated increased lateral instability on the narrow planks at the virtual roof environment. The dose–response increase of the T-AV with the reduced plank width most likely reflects the intensified use of the 'trunk-tilt' strategy for maintaining or recovering the lateral walking balance on narrow surfaces. The significant effect of surface width on the F-AV reveals the increased demand for ankle eversion/inversion control movements, i.e. 'foot-tilt' control strategy at the laterally restricted walking surfaces. This finding is consistent with an earlier study, which found increased activity in the lower leg musculature during constrained walking conditions (on a 15-cm plank) as compared with unconstrained walking conditions in older adults (Brown *et al.* 2002).

4.1.2. Shoe style and surface width interactions

The significant interaction of shoe style and surface width on T-AV underlines the significance of the sensory information from the feet and ankles. Thus, the increased T-AV for the running shoes, as compared to the tennis and the basketball shoes on the narrow plank, most likely reflects increased instability and elevated dependence on the 'trunk-tilt' control strategy. The excessive cushioning and inadequate motion control characteristics of the running shoes may have reduced the accuracy of sensory information and the effectiveness of the 'foot-tilt' strategy to generate adequate corrective responses. Further, the increased T-AV for the 'low-cut' shoes as compared to the 'high-cut' shoes indicates that the height of the shoe upper may be an important factor for improved lateral balance on the elevated narrow planks. Most likely the higher shoe upper provided more accurate and timely proprioceptive information of ankle joint motion and body orientation and thus reduced the need for large corrective responses at the trunk.

The significant interaction of shoe style and surface width on F-AV indicates the specific shoe lateral stability response to the intensified 'foot-tilt' control activity on the narrow planks. The greater shoe-style differences in F-AV on the narrow planks might be related to a number of factors, which determine the shoe motion control potential. Some of the important shoe motion-control-related characteristics include the shoe fit, the heel-counter stiffness, the heel lateral geometry and stiffness and the shoe torsional resistance (McPoil 2000, Reinschmidt and Nigg 2000). The lower F-AV for the tennis and basketball shoes corresponds well to the improved motion control properties of these shoe styles, which are generally characterised with wider, flatter heel soles and stiffer heel counter than the running shoes (Stacoff *et al*. 1996). In contrast, the higher angular velocity for the running shoe can be related to its inferior motion control properties. The increased cushioning of the running shoes may have reduced the sensory inputs from the feet and thus further contributed to the increase of T-AV in all experimental conditions.

4.1.3. Shoe-style and plank tilt interaction

The significant effects of plank tilt on T-AV and F-AV reflects increased compensatory movements of the upper body and the foot in response to increased instability on the tilted plank. During the single support phase on the tilted plank, the foot is everted or inverted respectively, which results in reduced width of the functional support area, modified and reduced range of motion and muscle force producing capacity from the non-optimal joint alignment (Simeonov *et al*. 2003). On the tilted surface, the leg orientation relative to the everted or inverted foot further generates substantial destabilising moments, which have to be compensated by proximal and distal lateral muscle responses. Furthermore, the ankle joint alignment on the tilted surface determines a path of the reaction force under the foot, which is in the vicinity of the shoe lateral boundary and thus increases the loss of balance risk.

The shoe-style and plank-lateral-slope interaction on F-AV revealed the specific functional role of selected shoe-design characteristics. Overall, the shoe styles with good motion control performed better on the tilted planks. The improved motion control characteristics allowed both more accurate sensory input (for detection of stability limits) and more precise and effective corrective responses. Further, the shoe styles with low-cut uppers were less affected by the lateral slope as compared to the high-cut shoes. However, the shoe style effects on F-AV at the tilted plank were relatively small and did not translate into significant ($p < 0.05$) whole body instability as measured by T-AV.

On the elevated tilted plank, the high upper may also interact with the ankle and induce instability. For example, the tennis shoe was less affected by the tilted plank, as compared to the basketball shoe. The adverse effect of the tilted surface on F-AV was even stronger ($p < 0.05$) for the safety boot as compared to the low-cut work shoe. Most likely, at the tilted plank the higher shoe upper interacts with the ankle to generate additional lateral forces and moments, which increased the rear foot angular motion. However, it is also possible that this effect is in part related to differences in the geometrical and mechanical properties of the sole. The design of a shoe for optimal walking balance control on sloped and narrow surfaces may require features providing good motion control in combination with a flexible high-cut upper.

4.2. *Perceptions of instability and shoe comfort*

4.2.1. Instability perceptions

Overall, the analysis of instability perceptions revealed similar effects as those for the angular velocities of the trunk and the ankle. Furthermore, the correlation analyses revealed a significant association between these parameters. The overall good correlation may indicate that the T-AV or the shoe angular velocity are sufficiently specific descriptors of instability, as well as that the instability perceptions are a sensitive and simple alternative measure. The perception of instability is a complex construct reflecting participants' feelings, thoughts and estimates on different aspects of balance control effectiveness and falling tendency. It is an integral characteristic involving many sensory sources, for body motion and orientation, including the movements of the foot and the trunk, and reflecting muscle activity, perceived effort and energy expenditure. The instability perceptions are highly subjective, since they rely on internal reference models, built and refined from previous knowledge and individual experience. However, previous research has demonstrated the validity and reproducibility of this rating method in simulated industrial tasks under various environmental conditions (Chiou *et al*. 1998). The fact that the workers could perceive the shoe-style effects in this study further suggests that a simple procedure could be developed for optimal shoe-style selection to improve walking balance on narrow planks at elevation.

4.2.2. Comfort perceptions

The comparable comfort ratings in the 'above average' range for all shoes, with the exception of the low work shoes, indicate that improved walking stability can be accomplished by proper shoe selection without sacrificing initial shoe comfort. The comparable shoe comfort ratings for the different shoe types and styles is most likely related to shoe design features, such as good cushioning and close-to-optimal sole flexibility and torsional resistance (Miller *et al*. 2000). Both the athletic and the work shoe styles were well cushioned and good cushioning has been directly related to increased comfort perception (Goonetilleke 1999). The work boots were very flexible and did not require initial 'breaking-in', which may have contributed to the comparable comfort ratings of the athletic and the work shoe styles. Further, the comfort ratings most likely also reflect the workers' expectations for the comfort level of a specific shoe type.

4.3. Limitations of the study

The present study may have some limitations, related to shoe selection and testing, walking surface parameter ranges, specific testing instructions and the virtual model.

The specific shoe style findings may not be generalised due to the wide variability in shoe properties. Further, the selected test shoes may not properly represent the shoe-style properties cluster centre, which is continuously changing with the ongoing improvements of footwear materials and design.

Since the tests were performed on new shoes, the results reflect more accurately the short-term, immediate effects of the shoe design. The research literature suggests that the motion control properties of athletic footwear deteriorate with time (Stacoff *et al*. 1996). Testing the shoes after longer service periods may yield different results. Future research studies are suggested to determine shoe deterioration limits for adequate balance control performance.

The plank width effects may not be directly extrapolated to surfaces narrower than the shoe. The study did not address the issues related to stepping on the edge of a narrow support surface. Stepping on an edge may result in lateral destabilising rotation of the foot. The extent of this additional instability depends on the relative position and velocity of the centre of mass projection relative to the surface edge. Shoe characteristics such as high-cut upper and increased torsional stiffness may be helpful to retain balance in such situations.

The effects of plank tilt may not be extended directly to the unrestricted sloped roof surfaces. Workers may use different strategies to walk on an unrestricted sloped surface, i.e. by laterally rotating the foot (abduction/adduction).

Some work activities on very steep-sloped roofs can be compared to climbing sport activities. The requirements for climbing sport shoes have been recently addressed (van der Putten and Snijders 2001). However, since roof construction work involves walking on sloped surfaces and narrow planks, the optimal footwear design for improved balance control may require a compromise solution.

Finally, the virtual roofing environment used in this study most likely resulted in reduced psycho-physiological fearful responses of the participants to the simulated height exposure as compared to a real height (Simeonov *et al.* 2005). Previous research reported that the heightened anxiety regarding the consequences of a possible fall is associated with reduced gait velocity (Brown *et al.* 2002). However, the virtual reality-induced instability had similar effects on gait – reduced gait velocity and shorter stride lengths (Hollman *et al.* 2006), which makes the simulated roof environment in this study a viable set-up for shoe style effects evaluation.

5. Conclusions

The study demonstrated that shoe style significantly affected workers' walking stability at elevated work environments. The challenging work environments, i.e. the narrow walking surfaces at virtual height, resulted in modified human walking strategies for balance control, which signified the role of the footwear in minimising the risk of loss of balance and fall. One possible direction for 'roofer shoes' would include the characteristics of tight fit, good motion control of the rear part and high flexibility of the front, moderate torsional stiffness and a very flexible high-cut upper. For the currently tested shoes, the high-cut work shoes, and more specifically the safety boots, would be the preferred choice for work on elevated narrow surfaces – they provide improved postural stability as compared to the low-cut work shoe types and the work boots. In addition to the improved postural stability, the safety boots provide the injury protection function (to the toe and the ankle). In conditions where safety shoes are not selected, the work boots would be preferred over the low-cut work shoes. Low-cut work shoes are not a good choice for work at elevated and narrow surfaces (especially if they are well padded). If athletic shoes are the choice, the basketball shoe type would provide additional benefit over the tennis shoe, due to the higher upper, through improved support and protection of the ankle as compared to the tennis shoe. The running shoe types would be less preferable for work at elevated and narrow surfaces since they are associated with greater instability and may increase the risk of losing balance. Although, on the sloped surface, the safety boots lost the advantage they had on the horizontal planks, they still provided similar walking stability as compared to the other work shoes and may be considered adequate for work on a low-slope surface. For work on steeper slopes, specialised work shoe design with flexible front, improved motion control at the heel and a flexible high-cut upper would be desired.

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