Towards Perceptual Fidelity: Slant Perception in Real and Interactive Virtual Environments

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An innovative motoric measure of slant based on gait is proposed as the angle between the foot and the walking surface during walking. This work investigates whether the proposed action-based measure is affected by factors such as material and inclination of the walking surface. Experimental studies were conducted in a real environment set-up and in its virtual simulation counterpart evaluating behavioural fidelity and user performance in ecologically-valid simulations. In the real environment, the measure slightly overestimated the inclined path whereas in the virtual environment it slightly underestimated the inclined path. The results imply that the proposed slant measure is modulated by motoric caution. Since the "reality" of the synthetic environment was relatively high, performance results should have revealed the same degree of caution as in the real world, however, that was not the case. People become more cautious when the ground plane is steep, slippery, or virtual.

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1. MOTIVATION

Measures of slant utilized in previous research were derived from a combination of verbal, visual, and haptic assessments of potentially limited ecological validity, e.g. such assessments were not based on involuntary human action. Verbal judgments were simply a verbal estimate in degrees of the hill's inclination in respect to the horizontal axis. Visual estimates were communicated via a disc which consisted of an adjustable angle representing the cross-section of the inclination of the hill, with a protractor mounted at the back. Haptic estimates were acquired by using a tilt board comprising of a flat palm rest, the tilt of which could be adjusted upward or downward to match the inclination of the hill. Studies of performance in both real and virtual environments (RE and VE) have

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demonstrated that visual and verbal estimates of geographical slant are largely overestimated, whereas haptic responses provide far more accurate estimates when participants judge slants, or hills, from a stationary point without actually walking on them (Bhalla and Proffitt, 1999; Creem and Proffitt, 1998; Proffitt et al. 1995; Proffitt et al. 2001; Ernst et al. 2000; Knill 1998; Thompson et al. 2005).

Kinsella-Shaw et al. (1992) presented a study in slant perception using the foot as a measure. A foot ramp was enclosed in a box consisting of two sidewalls, a back and top wall preventing the participant from seeing the foot's angle of inclination to the ground plane. The opening at the front permitted insertion of the foot, and the right foot could be rested at a particular inclination to the ground. Foot placement was such that the weight of the body was on the back foot. Following the placement of the foot, a large ramp of a given inclination was revealed and the task was to match the visible ramp inclination with the foot inclination. Participants instructed the experimenter to lower or raise the visible ramp until it matched the inclination of an occluded small ramp on which their right foot rested. Participants were able to report the inclination of the visual ramp quite accurately knowing when it was not at the inclination of the foot and proceeded to adjust it until it was. Such slant measures either utilize a specially constructed apparatus while participants perform a matching task using either their hand or foot, or verbally communicate the inclination.

Simulating slope on treadmill-style locomotion interfaces which communicate the impression of movement in large areas have been investigated in order to produce a sense of navigation (Hollerbach et al. 2001; Souman et al. 2010). Slant judgments have been acquired during exposure to simulation systems involving synthetic scenes in order to evaluate the perceptual fidelity of such systems in relation to real-world high level perceptual judgments and performance. Creem-Regehr et al. (2004) investigated the influence of action on slant estimates while varying the participants' potential of movement in a virtual environment. They conducted four experiments. In the first experiment they presented a virtual environment in which participants could shift their orientation, but not translation. In the second experiment in addition to freedom of rotation, participants experienced visual translation of the virtual world at a constant rate. During the third experiment, participants performed translational movements over level ground with the use of a sophisticated treadmill (Treadport). Finally, in the fourth experiment the Treadport was configured to operate on varied inclination levels that matched the inclination levels of the virtual world. In all experiments, the participants' viewpoint was returned to the same position before verbal, visual and haptic judgments of slant were communicated. In relation to the verbal estimate, participants were instructed to report a number in degrees that reflected the slope of the hill. For the visual measure, they adjusted a pie slice on a handheld disk to make the perceived cross section of the hill while holding it in the frontal plane. For the haptic estimate, participants placed the palms of their dominant hands on a tilting board that was sitting on top of a tripod placed about waist high. They were instructed to tilt the board backward to match the slope of the hill without looking at the palm board or their dominant hands as if they were placing their hands on the hill. In agreement with slant literature, this work concluded that in all conditions visual and verbal judgments were overestimated and haptic adjustments were more accurate. Additionally, walking with slope forces applied to participants via a torso harness led to increased perceptual overestimation of slant compared to the other conditions and existing literature, while the visually guided action remained veridical. Mohler et al. 2007 concluded that when participants wear an HMD they have a shorter stride length, slower walking velocity and a lower head-trunk angle than when their eyes are open and they are walking in the real world. Such gait parameters may be linked to caution while walking wearing an HMD because of its weight as well as its limited Field-of-View. This research analyzed specific gait parameters for a short period of time. It seems likely that over a longer period of time that the gait parameters may adapt and become more stable.

Environmental variability in relation to shadows, textures and lighting, enhances or diminishes visual realism in synthetic scenes (O'Sullivan and Howlett, 2004). It is tempting to replicate the real world as accurately as possible in order to provide equivalent experiences and performance (Waller et al. 2001; Fleming et al. 2003; Watson et al. 2001). Whilst arguably ideal, it is not yet computationally feasible for this to occur. Trade-offs between visual/interaction fidelity and computational complexity should be applied to a simulation system without detracting from its training effectiveness (Mania 2004; Mania et al. 2006; Adelstein et al. 2005, Mania et al. 2008). There is, therefore, a call for efficient techniques in order to assess the fidelity of a VE and determine its relationship to performance. The main goal is to economize on rendering computation without compromising the level of information transmitted (functional realism) (Ferwerda 2003; Mania et al. 2003; Mourkoussis et al. 2005).

The scope of the work presented in this paper is two-fold: we propose an innovative measure of slant based on gait establishing an action-based measure of perceived slant of stronger ecological validity than verbal or other measures reported in past literature. Moreover, we conduct a comparison study across real and virtual environments including material of differing friction in order to devise a perceptual fidelity metric for simulation systems, exploring simulation of equivalent performance rather than physical accuracy.

Existing literature related to human walking kinematics reports that human locomotion is analyzed in three distinct stages: the development stage (from rest to a certain velocity), the rhythmic stage (of constant average velocity) and the decay stage (coming back to rest). Reports from the rhythmic stage of free speed walking are consistent and a repeated cycle of gait events is observed. These events are named "foot strike" and "foot off". Therefore a gait cycle consists of the following four sequencing events: foot strike, opposite foot off, opposite foot strike, and foot off. Typically initial foot contact is at the heel, except in some cases or because of pathological gait where other areas of the foot, like the toes, may strike first (Rose & Gamble, 2006).

Taking inspiration from the biomechanics of gait, the measure proposed is based on every-day walking action eliminating constraints such as palm rests and foot ramps and will be referred to as ‘foot’ measure or, later, as ‘foot angle’. The foot measure is the angle of the foot (heel) during walking (see section 2.1.2 and Figure 2). This work explores the validity of the measure and if it is malleable to factors such as the materials of ramps that participants walk on, the degrees of inclination of the ramps, number of steps and the variability of measurements when the measuring task is repeated in both real and immersive virtual environments. We proceed to investigate the effect of varying rendering quality and modelling parameters such as material and texture of a computer graphics (CG) scene on perception of slant. Real-world surfaces of varied specularity such as tiles and carpet were simulated and displayed on a stereo capable Head Mounted Display (HMD). Each participant’s foot angle was measured while they were walking on real slopes. These slopes varied in surface material and participants either viewed the actual slopes or walked on the slopes while viewing a real-time CG scene of the slopes using a 3 degrees-of-freedom head-tracked HMD allowing for rotational tracking.

The paper is organized as follows: Section 2 discusses the methods and materials which are common for both real-world and VE foot measure experiments presented. Section 3 presents a summary of the real-world study introducing the proposed measure. Section 4 discusses the study that utilizes the same measure while immersed in a synthetic simulation of the real world scene where the first study was conducted. Section 5 provides the statistical results of two comparative analyses, e.g. foot measure accuracy in real vs. virtual environment. Finally, in section 6 we present a comprehensive discussion of the factors that affect the proposed measure of slant in real and virtual environments.

2. OVERVIEW OF THE EXPERIMENTS

The two experiments presented introduce the foot measure of slant based on participants' gait while walking on real slopes of varying surface material with no additional apparatus constructed. It is predicted that foot angles will be smaller and closer to the walking surface inclination when participants walk on more slippery or steep surfaces. It is also predicted that because of the high technological fidelity of the VE due to the immersive HMD and high quality rendering, the foot measure would correspond similarly with its equivalent in the real world indicating a high level of behavioural fidelity.

2.1 General Methods

This section describes the general methods applicable to both experiments to follow. Study-specific methods are discussed in the subsequent sections.

2.1.1 Participants.

Participants were recruited from the University of Sussex, UK undergraduate, postgraduate and other associated staff populations. Participants were naïve as to the purpose of the experiment. All participants had normal or corrected to normal vision and no reported neuromotor impairment. None of the participants of the virtual environment experiment had previously participated in the real environment experiment.

2.1.2 Stimulus and Apparatus.

Walking ramps were constructed. The length of each ramp was 122 cm. The ramps were designed to meet the following criteria: the inclination of the ramps should be such that participants are able to walk on them without dramatically changing their body posture; the surface materials should be of varying friction and also appear to be of varying friction and specularity. The walking ramps were viewed from the front. Both the RE and VE experiments were conducted in the same experimental room at the University of Sussex (Figure 1).

Fig. 1. Real environment (left), virtual equivalent (right)

The inclinations of the physical ramps were 0^o, 5^o and 10^o, as verified with a use of a protractor. The two conditions of varying friction were deducted after a set of pilot studies which demonstrated that perceived friction for a carpet material was significantly different compared to tiles.

Whilst participants walked on the ramps, a hidden camera video-recorded their gait and the associated foot angle was extracted from the video frames (Figure 2). The slant measure proposed is the angle of the foot derived in relation to the walking surface immediately before impact, referred to as 'foot angle'. The line runs between the lowest point of the heel and the lowest point of the ball of the foot. The ball of the foot (metatarsal) is indicated by Point 2 in Figure 2. Therefore, the foot angle can be defined as the angle formed by the walking surface and the imaginary line between the lowest two points of one's foot before it touches the surface. The foot angles were measured at the same time point for each participant. This was the frame preceding the participant's foot touching the surface.

Figure 2 illustrates the target images utilized to extract the foot angle for both heel strike and toe-metatarsal strike. The foot angles as derived in this particular instance are 13.7^{o} (Figure 2 left – heel strike) and -8.4^{o} (Figure 2 right – toe strike) respectively in relation to the ramp inclination. Foot angle measures were extracted from video frames using Adobe Photoshop®.

Fig. 2. Foot angle (heel strike -- left and toe-metatarsal strike -- right) with respect to walking surface.

.2.1.3 Procedure.

Both experiments were conducted in three consecutive stages: welcome, exposure to stimulus, and a debriefing session answering participants' questions.

Each participant was initially asked to read and fill-in a consent form. A verbal explanation of the experiment and the procedures to be followed were subsequently administered. Each participant was instructed that the experiment was concerned with recording people's reaction to walking on ramps and was directed to look at a video camera placed in front of them as much as possible. Pilot studies revealed the need to redirect attention away from the actual measure (i.e. the foot), as it was observed that participants often walked unnaturally when aware of their feet being recorded. Thus, the video camera used to record their steps was hidden from view. A camera placed in front of them served as a point of focus while participants walked on the ramp. In this manner, the biomechanical indicator of slant (the foot) was largely independent in relation to visual indicators of slant.

During the exposure phase, participants were asked to have a quick look at the walking ramp in front of them, i.e. the physical ramp in experiment 1 and the virtual ramp in experiment 2, and then take a few steps forward onto the ramp. Three steps were completed along the ramp in the real environment and one step while being immersed in the virtual environment for safety according to guidelines by the University's ethics committee. In the real environment, participants walked three steps and then they got off the slope by sidestepping. In the virtual environment, participants walked one step forward and then they got off the slope by stepping backwards.

Only first-step measurements were utilized for the comparative analysis between the real and the immersive environment. Participants were asked to repeat their walking task until instructed to stop. In order to take into account potential change over time, three repetitions were recorded per condition. Although requested to look at the camera in front of them as much as possible, they were also informed to look at the ramp as necessary for safety reasons.

3 FIRST EXPERIMENT: THE EFFECT OF SURFACE INCLINATION AND SURFACE MATERIAL ON FOOT ANGLE IN REAL ENVIRONMENTS

This experiment was designed to explore the effect of the perceived surface inclination and surface material on foot angle during walking in real environments. It was anticipated that the more specular or more steep the surface appeared to be, the closer to the inclination of the walking ramp the value of the foot angle would be, possibly indicating efforts of keeping stable while walking. If this was true, then the foot angle proposed would be a sensitive measure of slant and friction.

3.1 Method

Participants were exposed to six conditions in terms of inclination and surface material of walking surface and were required to walk on each slope according to such variations.

3.1.1 Design.

The experiment had four independent variables in a within-subjects design. The first variable was *MATERIAL* which had two levels: *carpet* and *ceramic tiles*. The second independent variable was *INCLINE* that had three levels: 0^o, 5^o, and 10^o. The third variable was *STEP* that had two levels: *step 1* and *step 2*. The fourth variable was *REPEAT* that had three levels: *repetition 1*, *repetition 2*, and *repetition 3*. The dependent variable was *FOOT ANGLE* (Figure 2). Participants were presented with six walking conditions. The order of presentation was counterbalanced. Figure 3 illustrates the six walking surfaces as captured from the hidden camera (side view).

Fig. 3. 0^o carpeted surface (top-left), 5^o carpeted surface (top-middle), 10^o carpeted surface (top-right), 0^o tiled surface (bottom-left), 5^o tiled surface (bottom-middle), 10^o tiled surface (bottom-right)

3.1.2 Participants.

Fourty-eight participants were recruited, as discussed in section 2.1.1. Twenty-five of the participants were male and twenty-three female. Thirty-six were of the 18-28 age range, ten of the 29-39 age range and two over 40's. The stimuli, apparatus and procedure were described in General Methods (Section 2.1.2, 2.1.3).

3.2 Results and Discussion

Foot angle scores explore the relationship of the proposed metric with the slope's inclination. For example, an angle of 2^o indicates that the metric overestimates the incline of the ramp by 2^o degrees, whereas an angle of -5^o indicates that the metric underestimates the incline of the ramp by 5^o degrees. Conceptually, a positive angle value means that the step was taken by the heel of the foot touching the ground whereas, a negative value indicates that the step was taken by the toes of the foot initially touching the ground, possibly because of caution. When the floor is slippery or slanted, one tends to walk in short/small steps and consequently the foot angle may be smaller.

The foot angle scores were analyzed using a factorial repeated measures model analysis of variance (ANOVA). Four independent variables were inserted in the model, i.e. *MATERIAL*, *INCLINE*, *STEPS* and *REPEAT*. Planned contrasts were designed to compare levels of the independent variables. On cases where the Mauchly's test produced significant values and the data violated the assumption of sphericity, the Greenhouse-Geisser estimate was applied to produce a valid F-ratio. Additional pairwise comparisons of the main effects were applied corrected using a Bonferroni adjustment. Table 1 provides descriptive statistics of the recorded data.

Table 1. Descriptive statistics of Experiment 1 - means and standard deviation (SD) of foot angle scores as a function of walking condition

			Carpet		**Tiles**	
Incline	**Step**	**Repeat**	**Mean**	**SD**	**Mean**	**SD**
0	1	1	8.84	6.54	6.02	7.94
		2	10.11	5.73	7.47	7.18
		3	10.92	6.05	8.78	7.87
0	2	1	9.02	6.46	5.54	6.24
		2	9.58	6.07	6.95	6.44
		3	9.20	6.36	7.16	6.92
5	1	1	6.15	7.09	5.83	6.29
		2	6.48	6.65	6.38	7.14
		3	7.17	6.71	6.89	7.74
5	2	1	4.55	6.66	2.87	6.21
		2	5.18	6.05	3.69	6.72
		3	5.96	5.02	3.99	5.69
10	1	1	4.62	5.83	3.66	5.54

		2	4.62	5.98	3.62	5.49
		3	4.37	6.03	3.69	6.84
10	2	1	1.24	4.80	-1.77	5.86
		2	1.35	6.06	-1.14	6.08
		3	2.09	5.63	-1.35	6.05

ANOVA analysis of the foot angle results revealed a significant main effect of *MATERIAL*, $F(1, 46) = 34.82$, $p < 0.001$. This effect indicates that independently of inclination level, step number and repetition number, participants' style of gait resulted in significantly smaller foot angles for the specular material (tiles) compared to the carpet material. Table 2 shows the mean foot angle scores and standard errors as a function of material.

Table 2. Descriptive statistics for the 'MATERIAL' main effect

			95% Confidence Interval	
MATERIAL	Mean	Std. Error	Lower Bound	Upper Bound
Carpet	6.19	.54	5.09	7.29
Tiles	4.35	.57	3.19	5.51

ANOVA analysis also revealed a significant main effect of *INCLINE,* $F(1.70, 78.25) = 121.43$, $p < 0.001$. The results reveal that the higher the incline of the walking path the smaller the foot angle relative to the ramp would be which is intuitively the case because of the joint constraints of the foot. Table 3 shows foot angle scores and standard errors as a function of incline.

Table 3. Descriptive statistics for the 'INCLINE' main effect

			95% Confidence Interval	
INCLINE	Mean	Std. Error	Lower Bound	Upper Bound
0 degrees	8.30	.55	7.17	9.43
5 degrees	5.43	.65	4.10	6.75
10 degrees	2.08	.53	1.00	3.16

Relevant to the main effect of *INCLINE*, post-hoc tests corrected using a Bonferroni adjustment reveal that the foot angle measurements were significantly smaller for the 5 degrees slope compared to the 0 degrees slope, $p < 0.001$, for the 10 degrees slope compared to the 0 degrees slope, $p < 0.001$ and for the 10 degrees slope compared to the 5 degrees slope $p< 0.001$.

ANOVA analysis also revealed a significant main effect of *STEP*, $F(1, 46) = 7.41$, $p < 0.05$. This effect indicates that independent of the material, the incline and the number of repetitions recorded, the second step provided significantly smaller slant measurements compared to the first step. Table 4 shows the mean foot angle scores and standard errors as a function of step.

Table 4. Descriptive statistics for the 'STEP' main effect

			95% Confidence Interval	
STEPS	Mean	Std. Error	Lower Bound	Upper Bound
First step	6.42	.73	4.95	7.89
Second step	4.12	.64	2.83	5.40

ANOVA analysis also revealed a significant main effect of *REPEAT*, $F(2, 92) = 9.27$, $p < 0.05$. This effect indicates that independent of the material, the incline and the step number, as the repetition number increases, the foot measure becomes higher, therefore, overestimating more the ramp incline. Table 5 shows the mean foot angle scores and standard errors as a function of repetition.

Table 5. Descriptive statistics for the 'REPEAT' main effect

			95% Confidence Interval	
REPEAT	Mean	Std. Error	Lower Bound	Upper Bound
First repetition	4.71	.55	3.59	5.83
Second repetition	5.36	.56	4.22	6.50
Third repetition	5.74	.54	4.63	6.84

Post-hoc tests corrected using a Bonferroni adjustment revealed that the foot angle was significantly lower during the first repetition compared to the second repetition, $p < .04$, and third repetition, $p < .03$. There was no significant difference, $p > .05$, when comparing the foot angle during the second repetition compared to the third repetition. It may be assumed that during the third repetition participants probably feel more comfortable walking on the ramp. This may be the reason why the foot angle is, in most cases, higher as the repetitions increase.

ANOVA analysis also revealed a significant two-way interaction of *MATERIAL* with *STEP*, $F(1, 46) = 8.72$, $p < 0.05$. This effect indicates that the type of material used had a different effect on the foot angle depending on which step was taken. A significant contrast was found $F(1, 46) = 8.72$, $p < 0.05$ revealing that the measure provided significantly smaller foot angle assessments for the tiles condition of the walking task compared to the carpet repetition during participants' second step in comparison to their first step.

ANOVA analysis also revealed a significant two-way interaction of *INCLINE* with *STEP*, $F(2, 92) = 11.87$, $p < 0.01$ indicating that the level of inclination affected the foot measure depending on whether the first or second step results are compared. A significant contrast, $F(1, 46) = 17.40$, $p < 0.001$, revealed significantly smaller foot angles of participants' second step compared to their first step, while walking on the 10^o inclination ramp in comparison to the 0^o ramp. An additional significant contrast $F(1, 46) = 8.62$, $p < 0.005$, indicated significantly smaller foot angles when participants took their second step compared to their first step specifically on the 10^o inclination ramp in comparison to the 5^o inclination ramp. Overall it could be concluded that the smaller foot angles observed during participants' second step as opposed to their first step is evident only while walking on the ramp of 10^o inclination.

4. SECOND EXPERIMENT: THE EFFECT OF SURFACE INCLINATION AND SURFACE MATERIAL ON STYLE OF GAIT IN IMMERSIVE VIRTUAL ENVIRONMENTS

This experiment was designed to explore the effect of the perceived surface inclination and surface material on foot angle during exposure to an immersive virtual environment which simulated the real-world room where the real-world experiment reported earlier took place. It was anticipated that the more specular the synthetic surface appeared to be through the Head Mounted Display, the smaller the value of the foot angles would be. Therefore, the specularity of the material in the synthetic scene would provoke similar motoric responses compared to the real-world study. Such effects would lead to the conclusion that the immersive simulation was *behaviourally* realistic in relation to its real world counterpart.

4.1 Method

Participants were exposed to six VE conditions in terms of inclination and surface material of walking surface. They were required to walk on the physical slopes while viewing an interactive environment displayed on a 3 degrees-of-freedom (rotational) head-tracked stereo HMD. The participants took only one step forward because of safety concerns, therefore, it was assumed that translational tracking would not offer additional valuable data compared to the utilized 3 DoF tracking.

4.1.1 Design.

The experiment had three independent variables in a within subjects design. The first variable was *MATERIAL* which had two levels: *carpet* and *ceramic tiles*. The second independent variable was *INCLINE* that had three levels: 0^o, 5^o and 10^o. The third variable was *REPEAT* that also had three levels: *repetition 1*, *repetition 2*, and *repetition 3*. The dependent variable was *FOOT ANGLE*. The order of presentation was counterbalanced. Figure 4 illustrates an example of the walking-visual conditions as captured by the hidden camera (side view).

Fig. 4: walking surface is wood; the visual surface is tiles.

4.1.2 Participants.

Fourty-eight participants were recruited, as discussed in section 2.1.1. Twenty-five participants were male and twenty-three were female. Thirty-eight participants were of the 18-28 age range, seven of the 29-39 age range and three ranged over 40's.

4.1.3 Stimuli and Apparatus.

Six virtual walking ramps were used as visual stimuli. The synthetic environment matched the apparent friction and slope apparatus of the initial real-world experiment. The physical walking ramps were represented in the synthetic scene by rendered carpet or tiles while participants walked on a physical plain wood surface while being exposed to the synthetic environment (Figure 5). The VE was presented in stereoscopic xVGA resolution (1024 x 768) on a Kaiser Electro-optics Pro-View XL50 HMD with a FOV of 50 degrees diagonal. An Intersense Intertrax2, three degree of freedom (DOF) tracker was utilized tracking the orientation of the participants' head. The non-perceptible latency of the tracker was 4msec. The viewpoint was set in front of the walking ramp. The viewpoint was set at an average eye-level height of approximately 170 cm and was retained constant. Each participant was instructed to look straight ahead and then the orientation was leveled to his/her horizon. Participants were completely secluded from the real environment by using black non-transparent material strapped around the HMD with velcro.

Fig. 5: Participant during exposure

The scene viewed through the HMD was a photorealistic simulation of the experimental room used in experiment one (Figure 1). The geometric model of the scene was imported into WorldUP, a proprietary virtual reality (VR) software authoring package. The applications ran on a standard PC.

4.1.4 Procedure.

The interpupilary distance (IPD) of each participant was measured with a common ruler during the welcome stage and the stereo application's parallax was adjusted based on individual IPD in order to reduce possible visual stress during exposure. Participants were advised to take only one step on the ramp for safety as indicated by the University of Sussex's ethics committee. The procedure followed is described in Section 2.1.3. The participants were able to see the virtual ramp but not the real ramp.

4.2 Results and Discussion

As before, the foot angles scores were analyzed using a factorial repeated measures model analysis of variance (ANOVA). Three independent variables were inserted in the model, i.e. *MATERIAL*, *INCLINE* and *REPEAT*. Table 6 provides descriptive statistics for the recorded data.

Table 6. Descriptive statistics of Experiment 2 - means and standard deviation (SD) of the foot angle scores as a function of walking condition

		Carpet		**Tiles**	
Incline	**Repeat**	**Mean**	**SD**	**Mean**	**SD**
0	1	-2.39	6.76	-1.92	6.51
	2	-2.02	8.85	-1.90	7.35
	3	-2.18	7.50	-2.27	8.00
5	1	-6.93	7.78	-6.12	5.83
	2	-3.46	8.18	-4.02	6.78
	3	-3.31	8.06	-3.05	7.14
10	1	-8.70	5.96	-8.73	8.28
	2	-3.47	6.59	-5.20	6.93
	3	-4.93	7.50	-4.80	6.24

ANOVA analysis of the foot measure results revealed that the type of material as displayed had no influence on participants' foot angle measurements, $F(1, 47) = .27$, $p > 0.05$. ANOVA analysis revealed a significant main effect of *INCLINE*, $F(2, 94) = 24.50$, $p < 0.001$. This effect indicates that the steeper the incline appeared to be, the smaller the foot angle was. In this experiment, the steeper the incline is, the larger underestimation of the ramp incline is observed. Table 7 shows the mean foot angle scores and standard errors as a function of incline. The foot angles have negative values in all three inclination conditions signifying toe or metatarsal strikes.

Table 7. Descriptive statistics for the 'INCLINE' main effect

			95% Confidence Interval	
INCLINE	Mean	Std. Error	Lower Bound	Upper Bound
0 degrees	-2.11	.95	-4.04	-.19
5 degrees	-4.49	.94	-6.38	-2.59
10 degrees	-5.97	.81	-7.60	-4.34

Post hoc tests revealed that the foot angles were significantly less underestimating the ramp's inclination while walking on ramps of 0^o inclination compared to ramps of 10^o, p

< .05 and 5^o, p < .05. As the inclination increases, the foot angle is underestimating more the inclination of the ramp.

ANOVA analysis also revealed a significant main effect of *REPEAT*, $F(1.73, 81.36) = 26.76$, $p < 0.001$. This effect indicates that independent of material and repetition number, participants' style of gait resulted in significantly different foot angles during each repetition. Post hoc tests revealed that foot angles were significantly lower, therefore, underestimating more the respective inclination during the first repetition compared to the second repetition, $p < .01$ and the third repetition, $p < .01$. There was no difference between angles during the second repetition compared to the third repetition, $p > .05$. Table 8 shows the mean foot angle scores and standard errors as a function of repeat. In all three inclination conditions the foot angles have negative values, potentially indicating caution.

Table 8. Descriptive statistics for the 'REPEAT' main effect

REPEAT	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1st repetition	-5.80	.78	-7.38	-4.22
2nd repetition	-3.34	.93	-5.22	-1.47
3rd repetition	-3.43	.90	-5.24	-1.61

ANOVA analysis also revealed a significant two-way interaction of *INCLINE* with *REPEAT*, $F(4, 188) = 11.43$, $p < 0.001$ (Figure 6). A significant contrast was found, $F(1, 47) = 21.04$, $p < 0.001$ revealing that the measure significantly underestimated the respective incline during the first repetition of the walking task compared to the third repetition when participants walk on the 10^o ramp in comparison to the 0^o ramp. Another significant contrast was found, $F(1, 47) = 24.32$, $p < 0.001$ revealing that the measure significantly underestimated the respective incline during the first repetition of the walking task compared to the third repetition when participants walk on the 5^o in comparison to the 0^o. Additional contrasts indicated that the foot measure significantly underestimated the incline of the ramp during the first repetition of the walking task compared to the second repetition when participants walk on the 10^o ramp in comparison to the 0^o ramp, $F(1, 47) = 25.55$, $p < 0.001$ and on the 5^o one in comparison to the 0^o one, $F(1, 47) = 11.93$, $p < 0.01$, respectively. Overall it could be concluded that the foot angles during the three repetitions were similar when walking at 0^o inclination, whereas at 5^o and 10^o inclination, during the first repetition participants did underestimate more the respective incline compared to the second and third.

Fig. 6. Interaction graph (INCLINE * REPEAT). The repeat is represented by the three lines: first repetition (red line), second repetition (green line) and third repetition (blue line).

5. COMPARATIVE ANALYSIS

Real vs. Virtual environment

The means of the foot angle scores associated with the first step were calculated across all repetitions, per walking condition of varied material and incline for the real and virtual experiment. Associated means were analyzed using a factorial mixed design ANOVA. Three independent variables were inserted in the model, two within-subjects, i.e. *MATERIAL* and *INCLINE* and one between-subjects, i.e. *GROUP* (real-world condition and VE). Table 9 includes the means of the foot angle scores across conditions.

Table 9. Descriptive statistics - means and standard deviation of foot angle scores as a function of walking condition

		Carpet		**Tiles**		
Incline	**Group**	**Mean**	**SD**	**Mean**	**SD**	**N**
0	Real	9.96	5.45	7.42	6.83	47
	Virtual	-2.20	7.11	-2.03	6.72	48
	Total	*3.81*	*8.78*	*2.64*	*8.25*	95
5	Real	6.60	6.39	6.37	6.29	47
	Virtual	-4.57	7.43	-4.40	6.21	48
	Total	*.95*	*8.90*	*.92*	*8.24*	95
10	Real	4.53	5.26	3.66	5.31	47
	Virtual	-5.70	5.80	-6.24	6.58	48
	Total	*-.63*	*7.54*	*-1.34*	*7.76*	95

ANOVA analysis revealed a significant main effect of *MATERIAL*, $F(1, 93) = 7.26$, $p < 0.01$. This effect indicates that independent of the inclination level and the group participants belonged to, the tiled material provoked foot angles which were 'closer' to the respective inclines than the carpeted material. Table 10 shows the means of the foot angle scores and standard errors as a function of material.

Table 10. Descriptive statistics for the 'MATERIAL' main effect

			95% Confidence Interval	
MATERIAL	Mean	Std. Error	Lower Bound	Upper Bound
Carpet	1.43	.56	.317	2.55
Tiles	.79	.58	-.357	1.94

ANOVA analysis also revealed a significant main effect of *INCLINE*, $F(1, 186) = 61.13$, $p < 0.001$. This effect indicates that independent of the material and the group, the foot angle for inclination at 5^o and 10^o were 'closer' to the respective inclines than at 0^o inclination. Table 11 shows the means and standard errors of foot angle scores as a function of incline across both viewing conditions.

Table 11. Descriptive statistics for the 'INCLINE' main effect

			95% Confidence Interval	
INCLINE	Mean	Std. Error	Lower Bound	Upper Bound
0 degrees	3.28	.62	2.05	4.52
5 degrees	.99	.63	-.26	2.26
10 degrees	-.93	.54	-2.01	.14

Follow-up post-hoc tests revealed that foot angles were significantly higher, while participants walked the 0 degrees slope compared to both the 5 degrees slope, $p < .01$ and the 10 degrees slope, $p < .01$. Foot angles were significantly higher while participants walked the 5 degrees slope compared to walking the 10 degrees slope, $p < .01$.

ANOVA analysis also revealed a significant main effect of *GROUP*, $F(1, 93) = 89.94$, $p < 0.001$. This effect indicates that participants' foot angles were significantly different in the real compared to the virtual environment. The results reveal that in the real environment participants overestimated the angle of the incline, whereas in the virtual environment participants underestimated the incline. Table 12 shows the means for the main effect of *GROUP* with the associated standard errors.

Table 12. Descriptive statistics for the 'GROUP' main effect

			95% Confidence Interval	
Group	Mean	Std. Error	Lower Bound	Upper Bound
Real	6.42	.79	4.84	8.00
Virtual	-4.19	.78	-5.75	-2.63

ANOVA analysis also revealed a significant two-way interaction of *MATERIAL* with *GROUP*, $F(1, 93) = 5.78$, $p < 0.05$. This effect indicates that the type of material used had a different effect on the acquired foot angle scores depending on whether participants took part in either the real or virtual environment. Figure 7 illustrates this interaction. The graph shows that the foot angle scores in the real environment overestimated the inclination of the ramps whereas in the virtual environment, they underestimated the inclination of the ramps. A significant contrast was found, $F(1, 93) = 5.78$, $p < 0.05$, The relative distance between the lines representing the two groups (i.e. real and virtual environment) in the tiles condition is significantly smaller than the distance of the same groups in the carpet condition (Figure 7). Overall the foot angle is closer to the ramp's inclincation whenparticipants are walking on tiles.

Fig. 7. Interaction graph (Material * Group). The Group is represented by the two lines: real (red line) and virtual (green line)

6. GENERAL DISCUSSION

The work presented in this paper introduced a novel action-based measure of slant in real and virtual environments. Treadmill-style locomotion interfaces which communicate the impression of movement in large areas could be evaluated in terms of their simulation fidelity through the accuracy of such action-based measures either when walking on tilted treadmill interfaces or when slant is displayed on a screen while walking on a flat treadmill interface. Of particular interest has been to explore whether the proposed measure is affected by factors such as: materials used for the walking surface; inclination of the walking ramps; steps number; and the variability of measurements when the walking task is repeated. The correspondence of the angle of the foot in the virtual world in relation to the real world could indicate high levels of behavioural fidelity of a simulation system derived from action-based perceptual judgments which are proven, here, to be sensitive to material and inclination variations. Further investigations including variations of the synthetic visual stimuli in terms of quality of rendering and ability of forward movement in the VE via 6DoF tracking could identify the necessary technological conditions for a simulation to produce accurate action-based assessments. In particular, it would be useful to include 6 DoF tracking in future experiments in order to verify that foot angles communicated in the VE will be unaffected when viewing a scene which is updated by even the limited forward motion of taking just one step. This is paramount towards positive transfer of training. This section discusses the main objectives of the studies in this paper and analyzes findings in relation to existing literature.

7.1 Effect of Material

In the real environment set-up of the first experiment, the proposed measure based on the angle of foot while walking proved to be smaller when the tiled material was used compared to when participants walked on the carpet material. These two materials have diverse reflective properties with the tiled material being shinier. Moreover, ceramic tiles are perceived to have lower levels of friction compared to a carpeted material. The smaller foot angles observed for the tiled surface could be explained either as an effect of participants perceiving slant differently due to the reflective properties of the material they were walking on or due to participants fear of losing balance when walking on slippery surfaces,or as a combination of both.

In the VE experiment, there was no effect of material on perceived slant. It could be argued that the reflective properties of the tiled material did not visually appear to be as dissimilar compared to the carpeted material, however, such effects should be investigated in a subsequent experiment which will utilize a scene investigating the perception of specular effects rendering. The simulation of reflective properties of materials or their impression, are significant parameters of behavioural fidelity. It has to be noted that in the VE participants did not actually see the surface they would be walking on prior or during the experiment. The surface they walked on while being exposed to the VE was a plain woodboard. Participants only received visual stimuli via the HMD. Therefore, they walked similarly in the VE while viewing rendered tiles compared to when viewing rendered carpeted surface. It could therefore be deducted that in the real environment it may be the specular effects visually perceived, potentially not rendered accurately due to resolution in the VE, that had an effect on the foot angle while participants were walking on materials of varied friction and not the actual levels of friction as sensed by the foot. Technological limitations which may play a role in slant perception between the real-world and VE may be the limited FoV as well as the weight and disruption of wearing the HMD. Detailed experiments which investigate technological issues separately by adopting a formal experimental design may be useful and should be conducted in the future. Further investigations allowing for more than one step in the VE should also be safely conducted. Moreover, the results reported here do not take into account cue conflict in the VE between what the participants feel under their feet and what they see, therefore, the effect of the fidelity of the match between what is seen and experienced should be explored.

7.2 Effect of Incline, Step and Repetitions

In the real environment, the foot angle was more smaller as the inclination increases. In the VE the foot angle was significantly more underestimated as the inclination increases. In the real environment, the proposed measure was significantly smaller during the second step compared to the first step.

The foot angles acquired in the real world were smaller and, therefore, ‘closer’ to the ramp inclination during the first repetition compared to the second or third, whereas in the VE experiment, the foot angles were ’closer’ to the ramp inclination during the second or third. Participants probably familiarized themselves with the apparatus and equipment during the first repetition and focused on the task during the second and third repetition. It is interesting to note that in both experiments the first repetition provided the smaller foot angle measurements compared to either the second or the third. In the real environment, the foot angles were positive numbers indicating that participants stepped on the walking ramp with their heel, however, in the VE the foot angles were all negative numbers indicating that participants stepped on the walking ramp with their toe or metatarsal as shown in Figure 2, potentially indicating more caution. In the real-world, the variation of foot angle between the first and the last two repetitions could be explained by participants exercising caution. In the VE, participants might have been adjusting to the VE apparatus during the first repetition and subsequently exercised more caution in terms of accuracy of their movements during the last two repetitions. One might also assume that participants should have been more cautious during the first repetition as they had not yet familiarized themselves to the equipment.

The experiments reported here indicated that the proposed action-based, walking measure of slant is influenced by: the material used on the walking ramps; the inclination of the walking ramps; step’s number; and finally the repetition of the walking task. Moreover, on average participants slightly overestimated the inclination of the walking ramp in the real environment (ME = 5.38, SE = .56), whereas participants slightly underestimated this inclination in the virtual environment (ME = -4.19, SE = .84). It should be noted that forward motion (translation) was not allowed for safety reasons while exposed to the HMD, therefore, only first-step foot angle measurements were compared. It should be investigated whether this discrepancy between the two environments gave rise to such conflicting results or whether participants walk differently in synthetic worlds. We suggest that the foot angle measure proposed depends on two variations: the inclination of the surface (since landing with one’s toes first would increase the chance of tripping) and the length of the stride – a long stride leads to a larger foot angle, for a constant ankle joint angle. Thus, long strides are likely to lead to steeper foot angles. It seems reasonable to assume that a walker’s degree of caution would have a strong effect on stride length – the more cautious a walker is, the shorter the likely stride length. Importantly, the results imply that the foot measure is modulated by motoric caution. Since the "reality" of the VR environment is relatively high, foot angle measurements were expected to be similar compared to the real-world revealing the same degree of caution as in the real world, but that is not the case in all cases as analyzed above, mainly attributed to the weak impression of reflective properties of materials. It seems reasonable to assume that a larger foot angle implies that the walker is confident and, therefore, potentially less cautious. On this interpretation of the results, people become more cautious when the ground plane is steep, slippery, or virtual. The foot angle proposed is, therefore, a sensitive measure of slant and friction while exposed to simulation systems.

7.3 Limitations and Future Work

You also say nothing about the reliability of the measure, i.e. repeatability of results. You should mention this as a limitation and hence, future work, to establish the usefulness of the measure.

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