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Effects of age related sensory degradation on perception of floor slipperiness and associated slip parameters

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Abstract

A laboratory study was conducted to determine how sensory changes in elderly people affect subjective assessments of floor slipperiness, and associated friction demand characteristics and slip distance. To relate these parameters to actual slip and fall incidents, 30 subjects from two age groups (young and elderly) walked around a circular track on the slippery and non-slippery floor surfaces, while wearing a safety harness to prevent injury in case of a slip or fall. Prior to the walking experiment, the Sensory Organization Test was performed. During the experiment, subjective assessments of surface slipperiness of the floor were obtained prior to walking and after walking on the floor. Slip distance, required coefficient of friction (RCOF) and adjusted friction utilization (AFU) were assessed utilizing motion analysis and force platform systems. The results indicated that sensory changes in the elderly increased the likelihood of slips and falls more than their younger counterparts. This was due to incorrect perceptions of floor slipperiness, and uncompensated slip parameters such as slip distance and adjusted friction utilization.

Keywords

Slips and falls; RCOF; Friction utilization; Perceived slipperiness; Sensory degradation; Gait; Aging

1. Introduction

Despite extensive effort in the area of slip and fall research by both ergonomists and the medical specialists, fall accidents continue to represent a significant burden to elderly individuals both in terms of human suffering and economic losses. Although sensory changes among older individuals have been reported by many researchers, research concerning the biomechanical analysis of gait parameters and ground reaction force and their relationships to sensory degradation have not been examined to date. Additionally, the relationship between subjective assessments of floor surface slipperiness and changes in biomechanical parameters of walking has not been examined. With a goal to further understand the complex dynamics of slip and fall accidents among the elderly, this paper addresses the relationships between intrinsic sensory changes associated with aging and biomechanical responses to slips and falls.

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A review of the literature on slip and fall accidents indicates that multiple mechanisms are involved in such accidents. In general, slip and fall accidents occur as a result of misjudgments of floor surface slipperiness and unadjusted gait/posture. Specifically, initiation of a slip occurs whenever the frictional force (F_μ) opposing the movement of the foot is less (e.g. due to contamination) than the shear force (F_h) at the foot after heel contact (Fig. 1). Hanson et al. (1999) reported that the number of slip and fall events increased as the difference between the required coefficient of friction (RCOF) and dynamic coefficient of friction (DCOF) of the floor surface increased. The RCOF is the calculated ratio of the horizontal foot force to the vertical foot force, and represents the minimum coefficient of friction that must be available at the shoe-floor interface to prevent initiation of slipping (i.e. initial friction demand). RCOF has been related to the tangent of the angle (θ, Fig. 1) between the leg and a line perpendicular to the floor (Perkins, 1978; Grönqvist et al., 1989). A fall can also occurs as a result of uncompensated posture or un-adjusted friction utilization during slipping (Lockhart et al., 2000a).

Tisserand (1985) suggested that frictional values are estimated and memorized unconsciously by individuals from preceding steps, thus forming an “observed” model of slipperiness. Further, this information is updated whenever perceptions of floor conditions are different from “expected.” This updated information is maintained by vision, proprioception, and the vestibular system (Nashner, 1982; Lacour et al., 1983; Pyykko et al. 1990; Dietz et al., 1991). For older adults, discrepancies between the model and reality may be greater than their younger counterparts due to age-related sensory degradations. Most medical researchers agree that sensory changes occur frequently in older persons (Stelmach and Worringham, 1985; Tobis et al., 1985; Tinetti and Speechley, 1989). Any age-related deterioration in visual, proprioceptive, and vestibular signals concerning postural control may produce a central signal detection problem, such as an inability to correctly perceive floor surface slipperiness before (visual) and after (tactile) walking on the surface. Misinterpreted floor surface slipperiness may interfere with compensatory gait regulation and protective responses, placing older individuals at a higher risk for slip and fall accidents (Clarkson, 1978; Kroll and Clarkson, 1978; Gottsdanker, 1980; Loveless, 1980).

Although much has been learned over the last few decades about sensory degradation among elderly individuals, still little is known about how these changes affect perceptions of floor surface slipperiness, and associated friction demand characteristics during ambulation over different floor surfaces. Thus, the objective of this research was to provide a better understanding of how sensory changes in elderly people affect subjective assessment of floor slipperiness, micro-slip distance, and resultant friction demands [i.e. RCOF and Adjusted Friction Utilization (AFU)] during ambulation over slippery and non-slippery floor surfaces. AFU is the measured ratio of the horizontal foot force to the vertical foot force at peak sliding heel velocity point, and represents the subject’s ability to adjust dynamic frictional requirements during slipping (Lockhart et al., 2000b). The specific research questions addressed by this study were: (1) can older and younger individuals correctly perceive floor surface friction prior to and after walking on the floor surfaces? And (2) does perception of floor surface slipperiness affect RCOF, AFU, and slip distance? It was hypothesized that sensory degradations among the elderly would increase the likelihood of slips and falls due to incorrect perceptions of floor slipperiness and un-compensated gait adaptations (as measured by RCOF and AFU) more than their younger counterparts.

2. Methods

2.1. Subjects

Six college students (three males and three females), and 24 elderly individuals (12 males and 12 females) participated in this experiment. The college students were recruited from the general student population at Texas Tech University, and the elderly subjects were recruited from a pool of volunteers at the Texas Tech University Health Sciences Center in Lubbock, Texas. Subjects' height, body mass and age distributions are presented in Table 1. Prior to participating in the experiment, elderly subjects were examined by a physician to ensure that they were in generally good physical health. Subjects also received a peripheral neuropathy examination in the Neurology Department at St. Mary's Hospital in Lubbock, Texas. Subjects were excluded from the study based on these tests (below 50% of the norm), and the physician's professional judgment.

2.2. Apparatus

Four different floor materials previously investigated by Myung et al. (1993) were used in the experiment: ceramic tile, stainless steel, oily plywood, and oily vinyl tile. Dynamic coefficient of friction (DCOF) values for each surface were measured using a lab-produced 4.54 kg (10 lbs) horizontal pull slip-meter with PVC sole mounting (7×12 cm) on the force platform. DCOF measurements were conducted at a constant velocity of 20 cm/s utilizing dynamometer. Averages of 10 measurements on each of four floor surfaces were used as a final DCOF values. Standard shoes with PVC soles were supplied to all subjects to maintain constant COF levels.

Walking trials were conducted on a circular track using an overhead fall arresting rig (Fig. 2). The circular wooden track was approximately 0.9 m (3 feet) wide and 20 m (66 feet) in circumference. The test surface of the simulated floor material covered approximately one-third of the track. A fall arresting rig was used to protect subjects from falling during the experiment. The rig consisted of a full-body parachute harness attached to an automated overhead suspension arm, and permitted subject to fall approximately 15 cm (6 in) before arresting the fall and stopping forward motion.

An ExpertVision Motion Analysis System was used to collect the three-dimensional posture of the subjects as they walked over the test surface. Ground reaction forces on the test surfaces were collected using two Bertec force plates. Posture and force plate data was sampled and recorded on a microcomputer at a rate of 180 Hz. The Sensory Organization Test (SOT) and Muscle Control Test (MCT) were performed using the NeuroCom NeuroTest System.

2.3. Procedures

The subjects attended a familiarization session before the walking experiments. During this session, the fall arresting system and walking conditions were introduced. Afterwards, the Sensory Organization Test (SOT) and Muscle Control Test (MCT) were performed to assess the balance profile and muscle latency (perturbation reaction time) of the subjects (Wolfson et al., 1992). Subjects were asked to stand on the NeuroCom dual force platforms with feet in the required position on the platforms while wearing a safety harness (Fig. 3). During the test, subjects were asked to close and open their eyes while the force plates moved forward and backward (translation), and also up and down (rotation). Individual measurements lasted 20 s, and the total testing period lasted 20 min. For the Sensory Organization Test, there were total of three trials for each of four conditions: condition 1=eyes open, stable platform; condition 2=eyes closed, stable platform; condition 3=eyes open, sway-referenced platform (e.g. platforms move with movement of the subjects' center-of-mass); condition 4=eyes closed, sway-referenced platform. For the Muscle Control Tests, there were two trials for each of six conditions: condition 1= small forward translation of the force plates; condition 2=medium forward translation of the force plates; condition 3=large forward translation of the force plates; condition 4=small backwards translation of the force plates; condition

5=medium backwards translation of the force plates; condition 6=large backwards translation of the force plates.

Prior to the walking experiment, retro-reflectors were attached to anatomically significant body positions: toe, heel, ankle, knee, and hip of the subject's left side. The heel target was placed on the outer-edge of the shoe (2.4 cm from the rear-edge and bottom of the shoe), and the target representing the toe was placed 2.5 cm above the sole, on the outer-edge. Floor samples were placed on the walking track prior to the walking experiment. For the oily conditions, high viscosity motor oil (SAE 40) was applied to the floor surfaces with a roller. During the walking experiment, each subject was asked to walk on the path of the track (on the floor samples) while wearing a safety harness. The ExpertVision Motion Analysis System and Bertec force plates were activated without the awareness of the subjects by a photoelectric switch.

Prior to and after walking on the floor surfaces, subjective assessments of surface slipperiness of the floor were obtained using a Perceived Slipperiness Rating Scale (PSRS) test. Subjects were asked to rate perceived slipperiness of the floor by looking at the surface prior to walking on the test floor surfaces (observed). Then, the subjects were asked to rate perceived slipperiness of the floor after walking on the floor (expected). During the experiment, the subject walked across each floor surface for 5 minutes. Within the 5-min trial session, two ground reaction force and postural measurements were recorded. Walking velocity for the experiment was based on cadence and set at: very fast—132 steps/min; fast —116 steps/min; average—100 steps/min, and slow—84 steps/min (cadence effects are not reported here). To reduce potential learning effects, each subject walked on a different floor surface on each of 4 different days, with at least 1 day of separation between each experimental session. Trials were ordered based on increasing DCOF (non-oily to oily), with the ceramic tile surface on the first day and the oily vinyl tile surface on the final day.

2.4. Experimental variables

There were two independent variables in the study.

2.4.1. Independent variables

1. *Age groups (2) (Between subjects)*. For this study, there were two age groups. Young (18–35 year olds), and old (65 years old and over).
2. *Four levels of floor surfaces*. A wide range of floor slipperiness from good to poor (unsafe) based on British Standard Institution was utilized and included; oily vinyl tile (DCOF=0.11), dry steel plate (0.38), oily plywood (0.16), and dry ceramic tile (0.29).

2.5. Dependent Variables

The converted coordinate data from the ExpertVision Motion Analysis System and force plate system were used to calculate slip distance and friction demands. A computer algorithm (written in Mathmatica 3.0) was used for calculation of these parameters.

1. *Perceived Slipperiness Rating Scale scores before and after*. The PSRS consisted of a number line ranging from 1 to 5, with whole and half number points marked on the line. A rating score of "1" meant the surface was "not slippery," while a rating score of "5" meant the surface was "very slippery." The subjects were told that they could use any of the whole or half points for rating each walking surface, thus allowing for a 9-point rating scale.
2. Friction demands

- **A.** *Required Coefficient of Friction (RCOF).* The ratio between the horizontal and vertical ground reaction force was calculated (peak 3, Perkins, 1978) on the dry steel and ceramic tile floors.
- **B.** *Adjusted Friction Utilization (AFU).* The ratio between the horizontal and vertical ground reaction force was calculated during slip-grip responses on the oily plywood and vinyl tile floors (Lockhart et. al., 2000a, 2000b).

3. *Slip distance*. The horizontal distance traveled by the foot after the heel contacted the floor was measured. The computer algorithm identified the slip-start coordinates as; when *Z* velocity (vertical heel velocity) reached minimum value after the heel contact, and slip-stop coordinates as; when *X* velocity (horizontal heel velocity) reached minimum value after the heel contact.
4. *Sensory Organization Test (SOT) scores*. Sensory Organization Test Scores were based on the assumption that a normal individual can exhibit anterior to posterior sway over a total range of 12.5° (6.25 anterior, 6.25 posterior) without losing balance. An equilibrium score was calculated by comparing the angular difference between the subject's calculated maximum anterior to posterior center-of-mass displacements to this theoretical maximum displacement. The result was expressed as a percentage between 0 and 100, with 0 indicating sway exceeding the limits of stability and 100 indicating perfect stability. Subcomponent scores of vision, vestibular, and proprioceptive systems were calculated via NeuroCom NeuroTest System utilizing SOT conditions (Section 2.2). Conditions 1 and 2 were used to test a subject's ability to use input from the proprioceptive system to maintain balance. Conditions 1 and 3 were used to test a subject's ability to use input from visual system to maintain balance. And, conditions 2 and 4 were used to test a subject's ability to use input from the vestibular system to maintain balance.
5. *Muscle Control Test (MCT) time*. The MCT time was defined as the delay (milliseconds) between the onset of a translation and the onset of the subject's active response to the support surface movement. The muscle latency time was based on the Motor Control Test protocols utilizing six conditions described in procedure section. The composite muscle latency time was determined as the average of the latency scores following medium and large translations.

2.6. Treatment of data

Gait parameter data [Slip Distance (SD), RCOF, and AFU] were analyzed first using a 2×4×4 (age×floor×cadence) three way repeated measures analysis of variance (ANOVA) on each dependent variable with $\alpha \leq 0.01$. The *P*-values in the ANOVA were adjusted for violations of assumptions regarding the variance– covariance matrix using the Huynh–Feldt method to estimate ε and adjusting the degree-of-freedom accordingly (Winer et al., 1991). Perceived Slipperiness Rating Scale scores before (observed) and after (expected) walking on four different floor surface slipperiness were analyzed using Wilcoxon matched-pairs signed-ranks test. SOT scores were analyzed using *t*-tests. Additionally, multiple regression analysis was performed by utilizing techniques available for evaluating probabilistic process, functional specification of mean response, constant variance and normality assumptions. The predictor variables were selected by utilizing Mallows' Cp and backward elimination procedure for dependent variable SD. Joint coordinates and ground reaction forces were digitally smoothed using a fourth-order, zero-lag, low-pass Butterworth filter (Winter, 1990). Residual analyses of the difference between the filtered and unfiltered signals over three different cutoff frequencies (6, 10, and 12 Hz) indicated 6 Hz as the preferred cutoff frequency.

3. Results

3.1. Perceived Slipperiness Rating Scale (PSRS) scores before and after

The results of the Wilcoxon matched-pairs signed-ranks test on each of the floor surfaces indicated that there were statistically significant differences between observed (before) and expected (after) PSRS scores on all floor levels for the elderly individuals, in contrast, there were no statistically significant differences between observed and expected PSRS scores on all floor levels for the younger individuals (Fig. 4; Tables 2 and 3). On the non-slippery floor surfaces (ceramic tiles and steel), observed PSRS scores for the elderly were consistently higher than the expected PSRS scores. On the slippery floor surfaces (oily plywood and oily vinyl tiles), observed PSRS scores for the elderly were consistently lower than the expected PSRS scores. Additionally, PSRS scores (both observed and expected) were higher for the slippery floor surfaces and lower for the non-slippery floor surfaces for both young and older individuals.

3.2. Friction demand (RCOF, AFU)

The ANOVA analysis of AFU indicated statistically significant age effect ($P \approx 0.0001$). AFU was higher for the older subjects (0.112) than younger subjects (0.103) on the oily vinyl tile floor surface (Fig. 5; Table 4). Additionally, older subjects AFU (0.112) was slightly higher than the DCOF of the oily vinyl tile floor surface. No statistically significant differences between young and older individuals (P=0.83) were found for RCOF.

3.3. Slip Distance (SD)

The ANOVA analysis of SD indicated statistically significant age effect ($P \approx 0.0001$). On average, the older subject's SD was longer (2.85 cm) than their younger counterparts (0.73 cm; Table 4).

3.4. Sensory Organization Test (SOT)

The result of the *t*-test on SOT scores indicated statistically significant differences between the young and old ($P \approx 0.0001$). The younger subjects (84.5%) had higher SOT scores, on average, than old subjects (71.9%). Itemized SOT scores (vision, vestibular, and proprioceptive) are presented in the Table 4. Older individuals sensory organization scores of vision, vestibular and proprioceptive system were lower than their younger counterparts.

3.5. Muscle Control Test (MCT)

The result of the *t*-test on MCT times indicated statistically significant differences between the young and old ($P \approx 0.0001$). The younger subjects (117.66 ms) had slower MCT time, on average, than old subjects (136.87 ms; Table 4).

3.6. Multiple regression analysis

Multiple regression analysis was performed to describe and predict the relationship between the independent variables (age, height, weight, SOT—vision, proprioceptive, vestibular responses, and MCT—for multiple regression analysis only) and the dependent variable slip distance (SD). The relationship between SD and sensory and physical parameters of the subject population was (R^2=0.40). The final model of SD is listed below:

$$\begin{gathered}\mathrm{SD}=9.49-0.23\,(\text{height})-0.08\,(\text{vision})+0.11\,(\mathrm{MCT}). \\ (R^2=0.40;\ P\approx 0.0001).\end{gathered} \tag{1}$$

4. Discussion

This research project was undertaken to provide a better understanding of how sensory changes in elderly people affect subjective assessments of floor slipperiness, micro-slip distance, and friction demands. In this section, the specific research questions addressed by this study will be elaborated.

> Question 1: Can older and younger individuals correctly perceive floor surface friction (DCOF) prior to and after walking on the floor surfaces?

Tisserand (1985) suggested that frictional values are estimated and memorized unconsciously from preceding steps and this information is updated whenever the subjects feel the floor conditions are different from what is expected. Furthermore, Swensen et al. (1992) and Tisserand (1972) reported that there is a strong correlation between DCOF values and subjective ratings of floor surface slipperiness.

Similarly, the results from this investigation also indicate that in general, subjective estimation of floor surface slipperiness was closely related to DCOF values of the floor surfaces (i.e. higher rating scores for slippery surfaces and lower rating scores for non-slippery surfaces). However, comparisons of PSRS for younger and older subjects indicated less agreement among elderly individuals in rating floor surface slipperiness compared to actual floor slipperiness than their young counterparts. Thus, the younger subject's model of slipperiness was more accurate than older subject's model in terms of effectively assessing different floor conditions (both observed and expected comparisons). Studies on the perceived slipperiness of floor surfaces (e.g. Chiou et al., 2000) have indicated that younger subjects are able to effectively perceive floor surface slipperiness, and also suggest that "perceived slipperiness rating scores" can be used to evaluate potential slip hazards. However, according to the results of this study, older individuals may not be able to accurately evaluate potential slip hazards associated with contaminated floor surfaces. Therefore, caution should be taken using perceived slipperiness rating scores to evaluate the potential slip hazards in working environments with older individuals.

> Question 2: Does perception of floor surface slipperiness and sensory information affect RCOF, AFU, and slip distance?

Ekkebus and Killey (1973) suggested that when potentially hazardous conditions are perceived through visual and tactile sensation, or expected to exist in a walking person's perceptual field, one's walking characteristics (i.e. friction demands) are adjusted accordingly. In other words, perception of floor surface slipperiness can affect RCOF. The results presented in Fig. 5 indicate that the RCOF on the non-slippery floor surfaces was adjusted to a level below the available DCOF for both the young and the elderly. Additionally, older individuals' RCOF was lower than the younger individuals. Lower RCOF of the older individuals may have resulted when floor conditions were perceived as more slippery (over compensation) than after walking on the floor surfaces (i.e. observed PSRS scores for the elderly were consistently [significantly] higher than the expected PSRS scores). Further work investigating the relationship between perceived slipperiness and gait compensation on RCOF is needed to elucidate this possibility.

AFU was adjusted to a level below the available DCOF of the oily plywood for both the young and the elderly, yet, older individuals AFU was not adjusted to a level below the available DCOF on the oily vinyl tile floor surface. This potentially dangerous situation may have resulted when elderly individuals misinterpreted floor surface slipperiness while slipping due to the sensory degradations, and resulting in longer slip distance. The prediction model (Eq. (1)) further supports that vision and reaction time were important for determining distance slipped. Whether this is a limitation of composite sensory degradations of vision, vestibular and proprioceptive systems or a result of physical limitations of vision and postural response is not clear from these results. More detailed examination of the physical and cognitive limitations [vision, gait adaptations prior to heel contact, postural responses during slipping, and psychophysical aspects (e.g. fear of falling) to walking on the slippery and non-slippery floor surfaces] would allow further understanding of the complex causes of age related slips and falls.

In conclusion, subjective frictional values were affected by DCOF of the floor surfaces, and, older subjects' model of floor surface slipperiness was less accurate than their younger counterparts. Consequently, older adults misinterpretation of floor surface slipperiness affected friction demand characteristic while slipping (AFU) and increased slip severity (SD).

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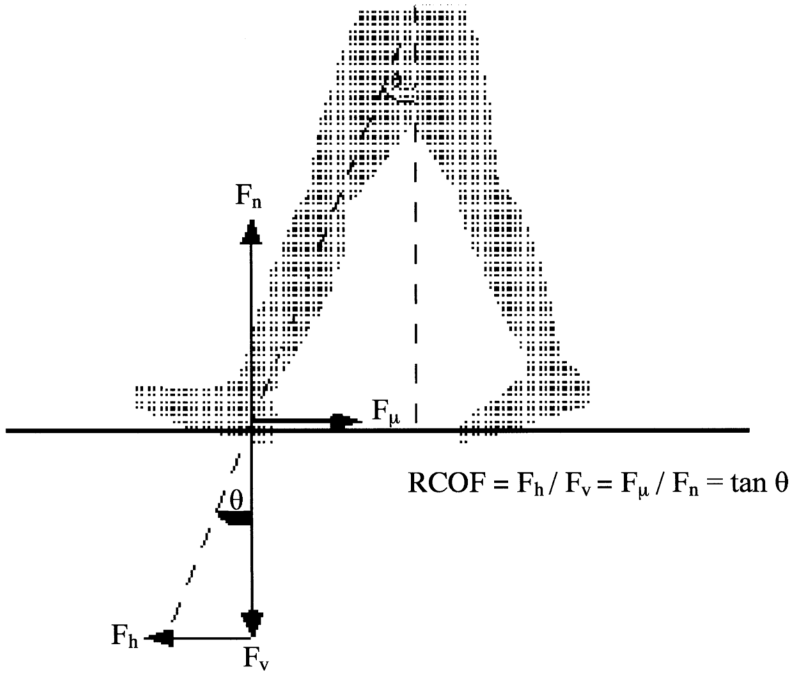

Fig. 1.
Force vectors applied by the left foot during the heel contact phase in normal level walking. (F_h=horizontal, F_v=vertical, F_μ=frictional, and F_n=normal force; adapted from Grönqvist et al., 1989).

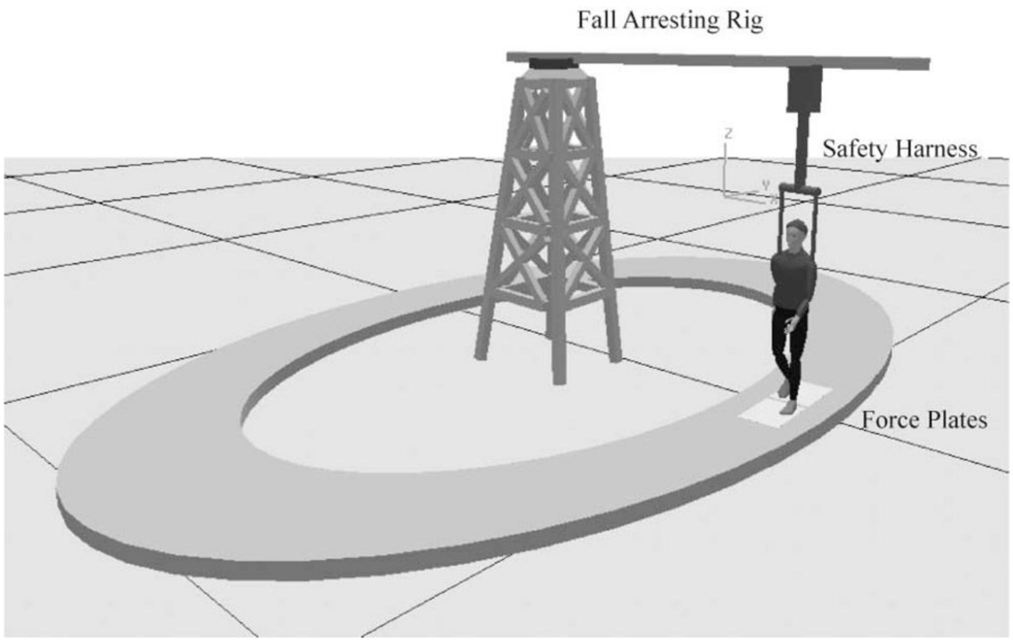

Fig. 2.
Field layout of the experiment including the safety harness, force plates, and fall arresting rig.

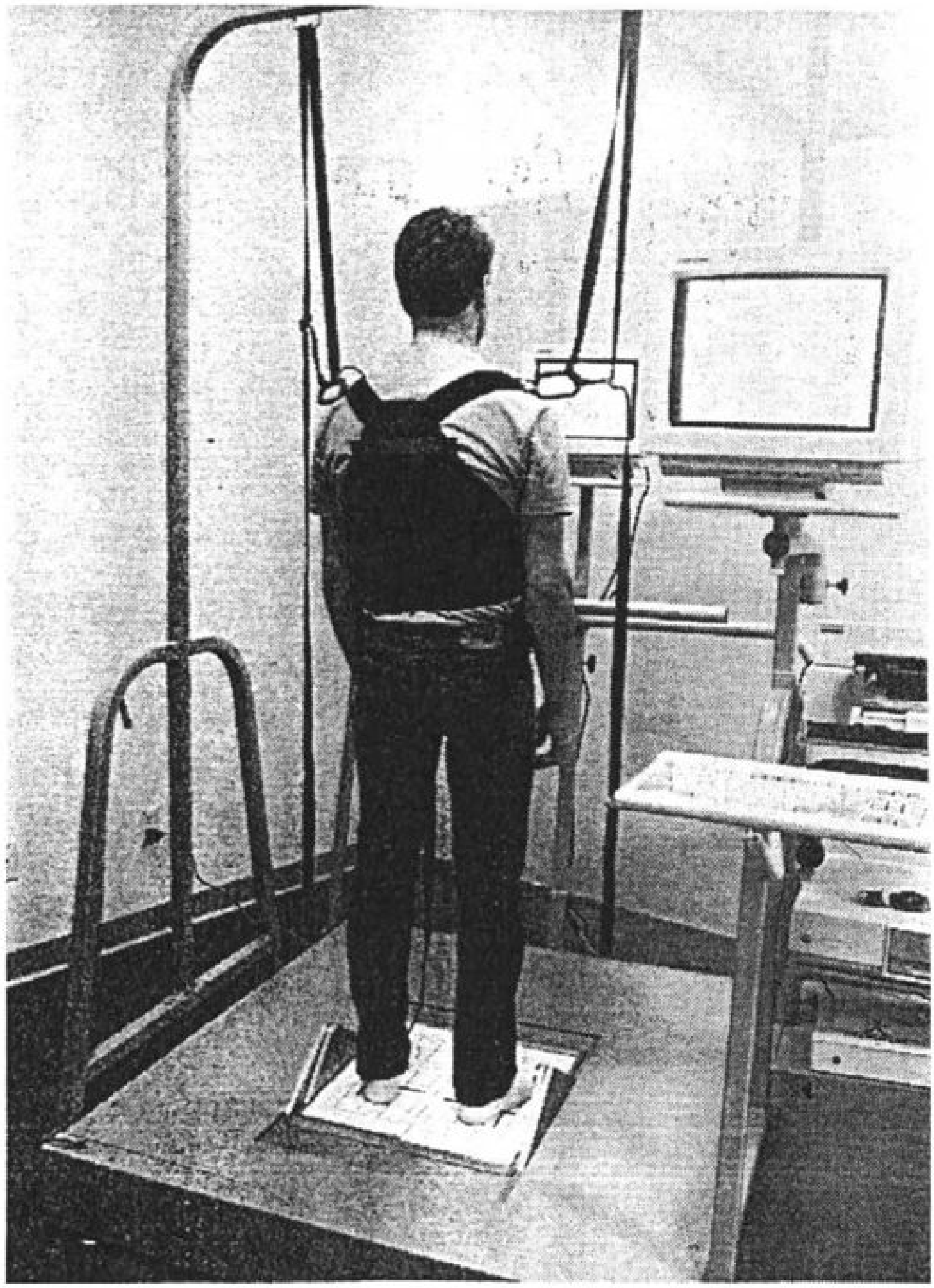

Fig. 3.
Layout of the NeuroCom system, including the force platforms, computer monitor and safety harness.

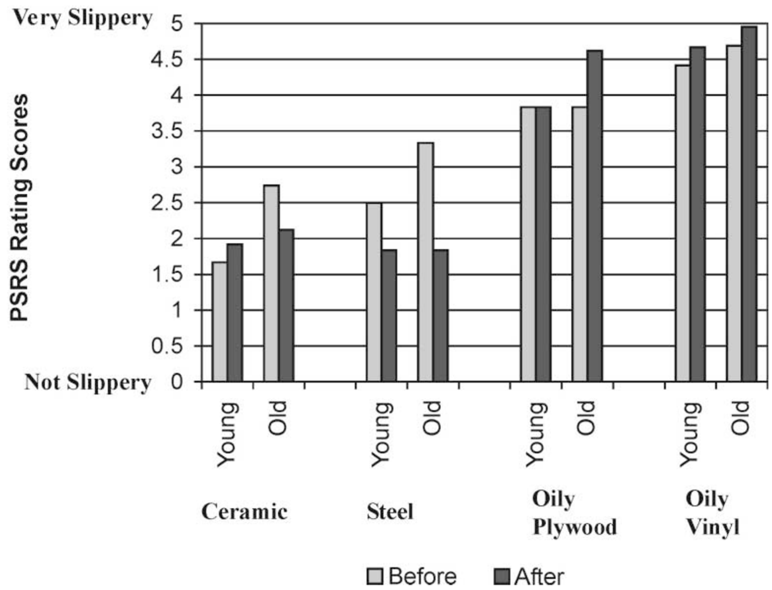

Fig. 4.

Mean perceived ratings scales scores before and after among young and older subjects on four different types of floors.

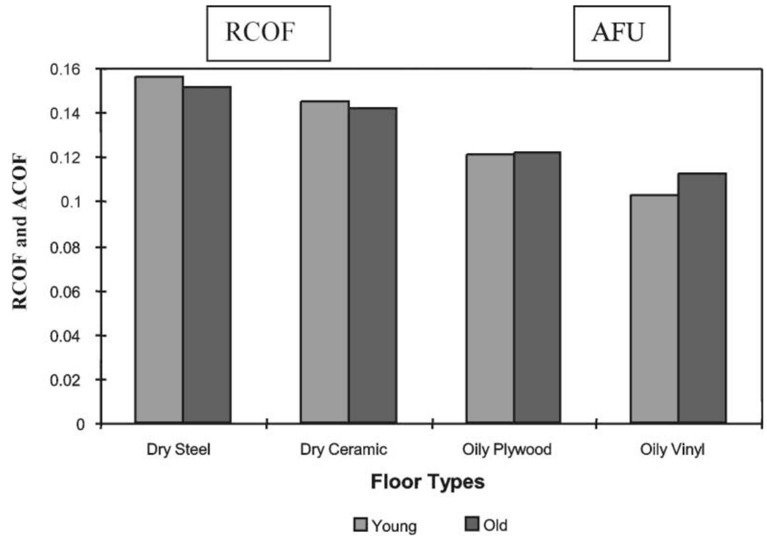

Fig. 5.
Friction demand characteristics on oily floor surfaces (AFU) and dry floor surfaces (RCOF) between young and the elderly.

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Table 1

Subject information

	Young (18–35 years)	Elderly (65 years and over)
	Mean (S.D.)	**Mean (S.D.)**
Age (year)	22.6 (2.0)	72.5 (6.9)
Height (cm)	169.7 (5.7)	174.1 (6.0)
Mass (kg)	63.5 (9.6)	74.4 (12.3)

Table 2

Mean and standard deviations of Perceived Slipperiness Rating Scale (PSRS) test scores (before and after) on four different floor surfaces between young and the elderly

Floor types	Young		Elderly	
	Before	**After**	**Before**	**After**
Ceramic	1.66 (0.16)	1.91 (0.22)	2.74 (0.43)	2.11 (0.28)
Steel	2.50 (0.37)	1.83 (0.21)	3.33 (0.58)	1.83 (0.21)
Oily plywood	3.83 (0.71)	3.83 (0.71)	3.83 (0.71)	4.61 (0.94)
Oily vinyl	4.41 (0.85)	4.66 (0.91)	4.67 (0.92)	4.95 (0.99)

Table 3

Wilcoxon signed ranks test on each of the floor surfaces (observed vs. expected) between young and the elderly[a]

Floor types	Young			Elderly		
	n	***T***$^{+}$	***p***	***n***	***T***$^{+}$	***P***
Ceramic	3	3	*0.625*	19	173.5	*0.0001**
Steel	5	15	*0.030*	18	170.0	*0.0001**
Oily plywood	2	2	>*0.625*	17	91.0	*0.0062**
Oily vinyl	3	6	*0.125*	7	28.0	*0.0078**

[a] where, *n*, number of ranked trials excluding no differences among observed and expected PSRS rating; T^{+-}, sum of fewest differences between observed and expected PSRS ratings; *P*, critical values of T^{+} for the Wilcoxon signed ranks test.

* Significant difference at $\alpha \leq 0.01$.

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Table 4

Summary of slip parameters and sensory information of young and the elderly

Variables	Young	Elderly
	Mean (S.D.)	Mean (S.D.)
Slip Distance (cm)*	0.733 (1.58)	2.85 (10.51)
RCOF	0.1314 (0.03)	0.1319 (0.03)
AFU*	0.103 (0.02)	0.112 (0.03)
SOT (%)**	84.50 (5.09)	68.58 (9.27)
Vision**	90.66 (6.77)	74.00 (18.50)
Vestibular**	79.66 (9.89)	47.50 (17.89)
Proprioceptive**	85.90 (5.19)	67.00 (11.97)
MCT (ms)**	117.66 (7.90)	136.87 (11.97)

* Significant difference (ANOVA) at α≤40.01.

** Significant difference (*t*-test) at α≤40.01.