# Ergonomic Design Issues and Carpet: A Review

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## ABSTRACT

**A critical literature review is presented that covers four ways that carpet can have an impact on the ergonomic design of the indoor environment. Specifically, the review examines how carpet affects the risks of slips and falls; how it affects standing comfort and fatigue; how it affects the thermal insulation of the floor; and how it affects the acoustic design of a room. Research lacunae and future opportunities are identified.**

### INTRODUCTION

Carpet has been used as a decorative and functional design element for thousands of years. Goats and sheep were sheared for their hair and wool which was spun and woven for rugs some 8,000-6,000 years BC. By 1500 BC the Egyptians were using looms for carpet weaving. Today in the USA, carpet accounts for some 72% of the total flooring market and over 1.6 billion square yards are shipped annually. Carpet has been an integral part of human life for millennia. Given this, it is surprising that research on the ways that carpet can affect the quality of our indoor environment is both scattered and limited.

The ergonomic design of the indoor environment can be impacted by carpet in four ways:

1. Carpet can affect the risks of slips and falls.
2. Carpet can affect standing comfort and fatigue.
3. Carpet can affect the thermal insulation of the floor.
4. Carpet can affect the acoustic design of a room.

This paper reviews the research literature on each of the above topics. It does not include information on other effects of carpet, such as on indoor aesthetics or indoor air quality.

### Carpet affects the risks of slips and falls

Slips, trips and falls are a source of serious injury and even death. After motor vehicle deaths, falls are the second leading cause of accidental death in the U.S., and annually there are some 12,000-15,000 fatalities from slips and falls in both occupational and non-occupational settings (Keyserling, 2000). The vast majority of these accidents occur in non-occupational environments, and the incidence and severity of the falls are age related (Isberner *et al.*, 1998). Two thirds of falls occur because of slips and one third of falls occurs because of tripping (Redfern *et al.*, 2001).

Falls are the leading cause of accidental death in the elderly, and in 1999 there were ~ 10,000 fatalities from falls among those 65+ years old (CDC, 2003a). In 2000, emergency departments treated 1.6 million seniors for fall-related injuries (*ibid*.). Between 20%-30% of those who fall will suffer a moderate to severe injury, such as a facture of a vertebrae, hip, forearm, leg, etc. (Sterling *et al.*, 2001). The annual direct medical costs of these fractures exceed $6 billion (Norris, 1992). Falls are also the leading cause of serious head traumas in seniors (Jager *et al.*, 2000). For all fall-related injuries among seniors, the costs exceeded $20 billion in 1994, and the costs are projected to exceed $30 billion per year by 2020 (Englander *et al.*, 1996). Some estimates put the annual total of

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direct and indirect costs in the range of $75-100 billion (Cali & Kiel, 1995). The risks of floor-related injuries are underestimated by both the elderly and those who design facilities for the elderly (Wells & Evans, 1996).

Age-related declines in sensory abilities, in strength and muscular coordination, and in postural stability all can contribute to the increased risk of falling. The severity of a fall injury is increased in seniors because of the osteoporosis that occurs with age. There is also evidence for changes in walking patterns with age. Of the falls that occur, hip fractures are particularly serious, and these accounted for 338,000 hospital admissions in 1999 (Popovic, 2001) and are projected to account for over 500,000 admissions by 2040 (Brainsky *et al.*, 1997). There are some 1.5 million seniors in nursing homes and as many as 75% fall annually, resulting in >1,800 fatalities (Rubenstein *et al.*, 1988, 1994). In addition to the direct consequences, a fall can also result in a reduced quality of life because of post-fall changes in physiological functioning, changes in ability, and the fear of falling.

It is possible to reduce fall injury risks by using various kinds of assistive or protective aids, for example by using walking frames or hip protectors (Cameron, 2002). However, hip fractures only occur in 2% of falls (Myers *et al.*, 1991), and hip protectors have no protective effect on other body regions. A more generalized benefit might be achieved by changing the floor surface by using carpet rather than a harder floor surface (Rowe, 2002).

Carpet can impact the risk of falls in several ways, including:

1. Carpet increases surface traction and eliminates the risk of slipping.
2. Carpet may change postural stability.
3. Carpet may change gait.
4. Carpet can be a shock absorber and decrease fall impact forces.

## Carpet and Traction

A comparison of outdoor carpet (Beaulieu 1/4” pile height Olefin) and vinyl tile (Armstrong) covered in soapy water found that for a rubber sole, the coefficient of friction (COF) for the wet, soapy vinyl was 0.13 whereas for the carpet it was 1.80, showing better traction with carpet (Bunterngchit *et al.*, 2000). The perception of floor slipperiness is significantly correlated with the COF of the floor surface (Chiou *et al.*, 2000). Knowing that there is a greater chance of slipping on a vinyl floor compared with rough floors can affect an older person’s gait (Cham & Redfern, 2002). Between 16%-27% of annual falls in nursing homes occur because of environmental hazards, including wet floors (Rubenstein, 1997).

Although increased floor traction is beneficial for walking, it may pose an additional difficulty for a wheelchair user. Studies have shown that, compared to walking, cardiopulmonary stresses are significantly higher for wheelchair users who are manually propelling their wheelchairs over carpet (Glaser *et al.*, 1981). Propelling a wheelchair over carpet requires between 36% and 56% more energy than propelling this over the concrete, depending on whether the tires are pneumatic or hard rubber (Wolfe, 1978). However, not all studies have found differences in energy costs for different tire designs (Wolfe *et al.*, 1977). The rolling resistance for a wheelchair is lowest for tile and higher for carpet, and the resistance is 2-3 times higher for a dense weave, deep pile carpet (Brauer, 1972 cited in Glaser *et al.*, 1981). Cardiopulmonary stresses for wheelchair locomotion over carpet are higher than for over tile (Glaser *et al.*, 1981; Van der Woude *et al.*, 1999). The use of an inappropriate carpet in a facility may present an obstacle to wheelchair locomotion. Architectural design guidelines on the use of appropriate floor coverings are needed.

## Carpet and Postural Stability

The ability to maintain balance is crucial to reducing the likelihood of falling. Balance is a complex process that declines with age. One way of measuring balance is to assess the degree of postural sway that occurs when standing erect and this has been shown to increase with age and to correlate with falling (Maki *et al.*, 1994). Dickinson *et al.* (2001) reported that when seniors closed their eyes their postural sway was significantly increased by standing on a residential carpet (36-oz, 1/2” pile height, 1/8” gauge, cut pile carpet on a rebounded polyurethane 6-pound density, 7/16” thick padding), and they suggested that carpet or any soft flooring somehow interferes with the sensori-motor mechanisms involved in balance. However, when seniors stand on commercial grade carpet (28-oz, 1/10” gauge, 100% nylon, 3/16” pile height, level loop carpet) there is no change in their postural sway (Dickinson *et al.*, 2002).

## Carpet and Gait

Gait changes occur with age. Some studies have found that seniors tend to have a shorter step length and broader walking base (Winter *et al.*, 1990), while others have failed to demonstrate a significant effect (Bunterngchit *et al.*, 2000). On slippery floor surfaces such as oily vinyl tile, people tend to shorten their stride, but seniors are less able to adjust their gait in such situations (Lockhart, 1997). Subsequent research has shown that there are gait changes associated with aging that affect the risks of slipping, specifically the following fact: in older subjects there is a higher horizontal heel contact velocity with the floor, step length is shorter and there are slower changes to the transitional acceleration of the body's center of mass as a slip occurs (Lockhart et al., 2003). Carpet has been shown to improve the gait in seniors when compared to walking on a vinyl floor (Wilmott, 1987, Bunterngchit *et al.*, 2000). Whether or not a load is being carried in the arms, walking over transitional surfaces, such as from carpet to vinyl flooring, has a greater effect on the gait pattern of seniors than does walking over a uniform surface (Bunterngchit *et al.*, 2000). The use of transitional surfaces indoors, such as from a carpeted hallway to a tiled bathroom or vinyl kitchen floor, should be minimized to reduce gait changes and the risks of tripping or slipping (*ibid*.).

Walking on carpet reduces the peak pressures on the feet when compared with a hard surface such as concrete, (Mohamed *et al.*, 2002). However, Hansen *et al.* (1998) found that walking or standing while wearing soft shoes on a hard floor is protective against lower leg edema, whereas the use of a soft mat had a negligible effect. Redfern & Holbein (1994) measured the activity of four leg muscles, tibialis anterior, soleus, quadriceps and hamstring, while subjects walked over different surfaces and found that in general muscle activity was lowest when walking on low pile carpet with a firm cushion.

## Carpet and Impact Forces

The floor surface has a significant effect on the severity of a fall injury and rigid surfaces result in more severe injuries (Cayless, 2001). Peak impact forces for soft floors compared with hard floors can be reduced by 23% (Maki & Fernie, 1990). Considerable research has been conducted to develop a safety floor system design (Penn State Safety Floor) that consists of a vinyl-tile-covered floor surface with numerous supporting columns to create a relatively rigid, continuous walking surface with less than 2 mm deflection during normal walking, but that deforms elastically to yield up to a 15.2% reduction in peak forces to the femoral neck of the hips during a fall-related impact, and then returns to its original shape (Casalena *et al.*, 1998a,b). This energy absorbing design is predicted to reduce the incidence of hip fractures, and the resulting direct cost savings yield a return on investment (ROI) of 10.5 years, and the total cost saving (direct + indirect) is predicted to yield an ROI of 11 months (Zacker & Shea, 1998).

Studies show that covering the floor with carpet will reduce impact forces. Booth *et al.* (1996) documented a relationship between the type of floor covering and the incidence of hip fractures in proportion to the percentage of falls (864 falls, 18 hip fractures). They compared five floor surfaces, these being concrete, PVC tile, three carpet types (4 mm pile, 4 mm loop and 7 mm), and found that the hip fracture incidence was lowest for the 7 mm carpet (~1%) compared with the harder floor surfaces such as PVC tile (~3.25%) and concrete (~6.25%). Other research has confirmed that pile carpet with a pad on a concrete floor reduces impact forces by ~7% compared with vinyl tile on a concrete floor (Gardner *et al.*, 1998). The difference in impact force is reflected by results from a study of 225 fall accidents which found that 17% of a group of patients who had fallen on carpet sustained injuries compared to 46% for a group where patients had fallen on to a vinyl floor (Healey, 1994).

## Carpet affects standing comfort and fatigue

Several studies have investigated the influence of floor surfaces on the body during long-term standing, and results show that softer floor materials usually result in less postural discomfort than standing on hard floor surfaces (Redfern & Cham, 2000).

Rys and Konz (1988) showed that heart rate (beats per minute) was higher after two hours of standing on a concrete floor (11.1 bpm) compared to carpet (95.2 bpm), and perceived comfort (scored from 100 points) was higher when standing on carpet (mean 77.7) than on concrete (mean 71.9). A similar finding was reported by Madeleine *et al.* (1997) who found that after two hours of standing, the intensity of unpleasantness was less and the comfort level was greater for a soft surface. Standing on a hard surface increased shank swelling, increased lower leg electromyography (EMG) activity (right soleus muscle), increased muscle fatigue, and detrimentally changed subjects' standing posture. There was less postural activity when standing on the soft surface, but this was still sufficient to prevent lower leg swelling.

## Carpet affects the thermal insulation of the floor

Because of its fibrous construction, carpet traps a layer of air close to the floor. Air is an excellent thermal insulator and consequently carpet acts to increase the thermal insulation of a surface. Additionally, a pad beneath carpet can further increase this thermal insulation effect.

Research conducted at the Georgia Institute of Technology School of Textile Engineering tested the thermal insulation values (R-Values) of carpet and cushion and found that the total R-value was more dependent on the total thickness of the carpet than the type of fiber content. Carpet alone and carpet with cushion combinations had R-values to range from 0.5 - 4.0. Results show that multiplying the total carpet thickness (in inches) by 2.6 approximates the carpet's R-value and these values are additive for any combination of materials (CRI, 1977).

Statistical analysis by the author[c] of the data from the report by the Georgia Institute of Technology School of Textile Engineering study, using multiple regression models, has determined the associations of carpet physical design variables and the R-values. Results show that R-values are not associated with the fiber type, style, pile weight, gauge, stitches/inch or tufts/inch$^2$. The resulting multiple regression equation ($R^2 = 0.778$; $F_{2,12}=25.58$, $p=0.000$) shows that the R-value is associated with pile height (inches) and yarn type (continuous filament yarn [0]; spun yarn [1]). The regression equation is:

$$\text{Insulation value (R)} = (0.84 \times \text{pile height}) + (0.364 \times \text{yarn type})$$

A carpet system (carpet and carpet pad) can increase the floor R value to somewhere in the range of 2 to 4. The energy cost savings of using a carpet system will vary with the type of floor construction, with the type of carpet system, and with the climate zone, the savings being greater in colder regions. For a wood floor construction, this range of carpet systems will improve energy efficiency between 6%-9%, which translates into an annual energy cost savings of $65-$200 given today's energy costs. For a concrete floor construction the same systems will improve energy efficiency between 8%-14%, which translates into annual energy cost savings of $80-$650.

## Carpet affects the acoustic design of a room

The acoustical performance of a room depends on many variables, including the characteristics of the flooring. A hard, flat floor surface acts as a sound reflector which increases the reverberation time of sound in the room. A hard floor also acts as a source of impact noise from footfalls, etc. A soft surface can act as a sound absorber and also dampen any impact noise in a room. Carpet, and especially carpet plus carpet cushion, can provide excellent sound absorptive surfaces that work as noted above.

The relevant measures of room acoustics are:

Sound pressure level (SPL) - usually measured in decibels (dBA – the A weighted scale most closely approximates the characteristics of the human auditory system).

Sound absorption coefficient ($\alpha$) - the incident sound energy fraction that is absorbed by a material at a specific frequency.

Noise Reduction Coefficient (NRC) - the average of the sound absorption coefficients at 250, 500, 1000, and 2000 Hz. The NRC is used to grade the sound control effectiveness of a material. An NRC of 1 will absorb all the sound energy.

Sound Transmission Class (STC) - sound transmission through walls, floors, and other barriers is measured at the 16 1/3 octave bands. Transmission is greater for low frequency sounds than for high frequency sounds. STC is a

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[c] Analysis undertaken by Hedge using Statistical Package for the Social Sciences v11.5

single-number rating that provides an estimate of the sound transmission performance of a partition in certain common sound insulation problems. Higher STC values indicate lower sound transmission.

Impact insulation class (IIC)[d] - a single-number rating derived from measured values of normalized impact sound pressure levels that estimates the impact sound insulating performance of a floor-ceiling assembly.

- Impact Noise Rating (INR)[1] - a single figure rating of the sound insulation provided by a floor-ceiling assembly from an impact noise. Assemblies rating more than zero (plus INR) are deemed superior.
- Reverberation Time ($T_r$) – reverberations are the sounds that persist in an enclosed or partially enclosed space after the source of sound has stopped emitting sound. $T_r$ is the time period required for sound level to decrease 60dB after sound source has ceased.

For a room with a concrete subfloor the addition of a commercial cut pile carpet (36 oz face weight) has been shown to increase the NRC by 0.25, and the addition of this carpet plus a commercially bonded polyurethane cushion increases the NRC to 0.55 (AFPF, http://www.afpf.com/sound_absorb.pdf). A test of the IIC showed that this increased from 19 for bare concrete to 58 with the addition of the commercial carpet and to 69 with the addition of the carpet plus a commercially bonded polyurethane cushion (*ibid*.).

## Classroom acoustics: effects of carpet

There is evidence that U.S. classrooms are too noisy and that inadequate classroom acoustics can adversely affect student performance (Herbet, 1999; Nelson, 2000). Effects of inappropriate reverberation times seem to be particularly important (Crandall & Smaldino, 2000).

A long reverberation time ($T_r$) creates poor classroom acoustics that may adversely impact learning. Classrooms should have a $T_r$ in the range of 0.4-0.6 seconds (Technical Committee on Architectural Acoustics of the Acoustical Society of America, 2000). “Soft” materials, such as carpet and acoustical ceiling tiles, increase sound absorption and decrease the classroom $T_r$. Carpet absorbs sound, reduces surface noise (e.g., footsteps and furniture movement) and helps block sound transmission.

Cunlif (1967)[e] evaluated the effects of carpet in two Los Angeles schools and concluded that the use of carpet reduced noise transfer between floors of the school, that carpet has better appearance than vinyl tile, that teachers reported that the sonic environment was superior in carpeted classrooms, and that the teachers reported that the carpeted classrooms were more conducive to learning.

The performance of 156 1st, 3rd and 5th grade children on the Standard Progressive Matrices (SPM) problems was compared for quiet (40dBA) and noisy (70dBA) conditions (Christie & Glickman, 1980). Classroom noise was presented via a stereo system to children who were tested in the school library. Results showed that the effects of noise did not vary with age, and older children fared no better at filtering out distracting noise. Task performance improved with age, as predicted. However, there was an interaction of noise and gender on performance: girls tended to perform better in quiet classrooms, while boys tended to perform better in noisy classrooms.

Edmonds and Smith (1984) studied the effects of classroom noise (70dBA noisy vs. 40dBA quiet conditions) on 289 sixth grade students. They compared results by student’s gender and intelligence level. Student performance was assessed using the SPM and the STEP reading test Form 3 (STEPIII). Overall, no gender differences were found and students who experienced the low noise condition outperformed those in the high noise condition. However, there was an interaction of noise and intelligence for the STEP III scores; students of above average intelligence performed worse during noise whereas those of below average intelligence performed slightly better during noise. It

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[d] The IIC and INR rating systems have different numerical scales. INR values can be positive, zero or negative. IIC ratings can only be positive numbers with higher values indicate greater sound insulation. Adding 51 to the plus or minus INR number approximately transposes INR ratings to IIC ratings.

[e] Report cited in on-line educational database, but appears to be unpublished.

is well known that for some people and tasks, short-term noise exposure can have an arousing effect; however, over the longer term, noise exposure invariably results in a performance decrement.

Finitzo-Hierber and Tillman (1978) compared monosyllabic word discrimination ability for twelve normal hearing children (8 to 12 years old) and twelve hearing-impaired children (8 to 13 years old) in different room acoustic conditions. Increasing the reverberation time resulted in an 18% performance decrease for the normal hearing children and a 38% performance decrease for the hearing-impaired children. In a "relatively good classroom listening environment (SNR = +6 dB; RT = 0.4 second)," children with normal hearing correctly recognized 71% of the spoken message and hearing-impaired children correctly recognized 59 % of the spoken message.

Research projects from 1996 and 1997 conducted by researchers at Heriot-Watt University in Scotland found that in classrooms with hard surfaces 15-50% of voice consonants uttered by teachers are lost in echoes. A study of 300 children (5-12 years) tested pupils' ability to discriminate of simple, familiar, monosyllabic words in quiet and in classroom noise. In classroom noise the discrimination error rate was 45.3% and this effect was most pronounced for children 7.5 years old (Smyth, 1979).

Research on improving classroom noise has tested whether reduced noise affects the development of pre-reading cognitive skills (number and letter recognition; letter-sound correspondence; rhyming) for 90 pre-school children (4-5 years old) who were tested before and after sound attenuation work in their classrooms (Maxwell & Evans, 2000). In each classroom there was only a small carpeted area, and most of the acoustic treatment involved the use of ceiling suspended sound baffles, which created quieter classroom conditions (~5dBA quieter). Recognition of numbers, letters and simple words significantly improved after acoustical improvements.

Research also shows that unsatisfactory classroom noise affects speech recognition, which in turn may hamper learning. In a relatively poor but commonly reported classroom listening environment (SNR = 0 dB; RT = 1.2 seconds), speech recognition scores dropped to less than 30 percent (Crandell & Smaldino, 2000). These detrimental effects may be greater for children for whom English is not their native language. "Less than acoustically optimal conditions in the classroom affect the academic performance of all students, but they pose a particular challenge for students learning in a non-native language, coping with learning disabilities, or hindered by impaired hearing. Studies show that such students suffer socially and behaviorally as well as scholastically" (Nelson & Soli, 2000)

A recent standard for classroom acoustics (ANSI S12.60-2002) sets specific acoustical background sound-level limits in classrooms that are significantly lower than those typically found in classrooms today, and it specifies that the maximum background sound level for an unoccupied classroom must not exceed an ambient noise level of 35 dBA and a reverberation time of 0.6 to 0.7 seconds. However, a recent study of classrooms in Ohio measured reverberation time and background noise levels in 32 unoccupied elementary school classrooms in 8 public schools in central Ohio, and most classrooms did not comply with ANSI S12.60-2002 (Knecht *et al.*, 2002). A recent unpublished study (Campos, 2003)[f] studied the effects of improvements to classroom acoustic conditions. Conditions were improved by installing a suspended ceiling (NRC of 0.70), applying a wall treatment across the top portion of the back wall, reducing windows size and installing secondary glazing. These acoustical treatments reduced $T_r$ from 2.6 seconds to 0.6 seconds and background noise levels during peak street noise hours from 66 dB to 38 dB. Teachers reported an 80% increase in satisfaction and fewer voice problems. After the acoustical treatment, 34.7% of total teacher absences were due to voice/throat problems compared with 57.5% before the treatment. Parents also met in the untreated and treated classrooms and decided to conduct their weekly association meetings in the treated classroom.

Children's learning may be disrupted in noisy classrooms that do not meet the ANSI S12.60-2002. Unfortunately, there remains a paucity of systematic research on the impact of carpet on classroom acoustics, on children's learning and on the impact of carpet on teachers' well-being.

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[f] Campos, M. (2003) Quiet in the classroom, http://www.armstrong.com/common/c2002/content/files/4250.pdf

## CONCLUSIONS

As this review has shown, the research literature is peppered with studies suggesting beneficial effects of carpet on ergonomic design variables, but there remains a dearth of systematic and cohesive research studies of the effects of carpet on the four issues identified, namely:

- How does carpet affect the risks of slips and falls?
- How does carpet affects standing comfort and fatigue?
- How does carpet affect the thermal insulation of the floor?
- How does carpet affect the acoustic design of a room?

The evidence that has been gathered suggests that carpet may offer several benefits for indoor environments, but confirmatory studies of these benefits generally are lacking. Future research on the effect of carpet on the ergonomic design of interiors should focus on filling these lacunae.

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