RELATING STAIR NOSING PROJECTION, TREAD RUN DIMENSION, SHOE GEOMETRY, DESCENT BIOMECHANICS, USER EXPECTATIONS, OVERSTEPPING MISSTEPS, AND CLOSED-RISER HEEL SCUFF MISSTEPS

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Closed-riser scuff marking is a long-lasting, easy-to-see (and document) indication of potentially serious deficiencies in stair design and construction, including run and nosing projection dimensions. Little is scientifically known about such marking—*and the relatively common heel scuff missteps they record*. Heel scuff missteps can affect other missteps, such as when foot placement overcompensation leads to an overstep on short treads. Generally, interactions among stair step geometry factors have not been well addressed in laboratory-based studies—*e.g., those utilizing motion capture methods*, in falls literature, and in codes and standards, a situation this paper addresses by illustrating (as a provocative proposal) how greatly improved nosing projection geometries might help mitigate the inherent dangers of short step run dimensions—*if geometry and gait considerations are further refined and confirmed by systematic studies.*

Introduction

In an accompanying paper for the International Conference on Fall Prevention and Protection (ICFPP2013) Pauls and Barkow (2013) describe stair-related fall risks and their interactions. The relatively abstract nature of their treatment is complemented by the graphic treatment provided below to illustrate relatively common missteps (described by Pauls, 2007) and interactions of various factors controllable through design, and related mechanisms such as codes and standards.

The focus here is on the foot-stair interaction, more specifically how the geometry of the step nosing (defined as the leading edge of the tread) and, more generally, the intersection of the step tread and the closed riser geometry below it, might be optimized to provide user's feet with the best possible support within standard limits of step run (measured horizontally, nosing-to-nosing).

As described by Pauls and Barkow (2013), run dimensions should be at least 280 mm for reasonable safety, but codes permit them to be as little as 210 mm in Canadian homes (even 150 mm in Japanese homes); hence a focus on home stairs, although the principles do apply broadly.

Given the discrepencies—*and safety consequences*—of relatively short step runs in relation to good standards, important questions are raised. First, what can be done with the many existing steep stairs to make the best of bad situations that, typically, are not easily rebuilt due to the space implications and existing construction context? Secondly, how can a stronger case be made for improving the codes and standards for adequate step run dimensions?

Step nosing projection might provide a partial answer for both questions. That answer could cut two, opposite ways. Either increased nosing projection, combined with special attention to the geometry and surface of the closed riser, will help or it will be shown to cause other problems.

While this paper provides a fairly graphic, introductory approach to addressing this, it is clear to this author that we need to invest in laboratory studies where the trajectory of people's shod feet on stairs can be meticulously documented and analyzed. Motion capture technology can provide the needed documentation if proper test facilities are available for carefully planned, human subjects testing. This is increasingly standard at major laboratories worldwide that are represented at ICFPP2013 by key researchers and program leaders. Thus the means exist. Does the organizational motivation and research support exist to take us beyond the current literature and whatever simple insights emerge from this paper?

An important clarification (evident from the graphics herein) is that the author did not use modern motion capture technology for this paper. The methods employed could have been used many decades ago. Video-based methods (which could have used film also) were used.

Without taking up a lot of this paper for literature review, incomplete mention is made of work by Japanese colleagues dating back to the last time the author visited Japan, the 1980s. Two of them could easily serve as co-authors of this paper given even their early work on stair step geometry (Kose, 1985; Nagata, 1985), two references that hardly do justice to their extensive research output and worldwide influence via highly valued interactions with many researchers.

A report devoted to nosings, especially proprietory ones, was by Roys and Wright (2003); much of its focus was on tread-nosing interface rather than the nosing-riser interface.

Key literature and resulting early, *conflicting* conclusions from it were relatively well captured by Templer (1992) and are now adding to some confusion, offset by much evidence-based guidance, in codes and their application to stair design and construction. At the risk of quoting too much, on one hand, or too little, on the other hand, here is the gist of what Templer (1992) wrote (with one interrupting comment). Note: Templer uses “nosing” with two different meanings, reflecting widespread confusion about the term which now means “the leading edge of the tread.”

> **7.2. 10 PROJECTING NOSINGS**
>
> Nature of the danger: The idea of projecting the front edge of the tread beyond the face of the riser below developed long ago. It offers a partial solution to the problem of narrow treads without increasing the overall depth of the tread. . . . Clearly there is a conviction that nosings are a necessary safety device. . . . studies suggest that nosings greater than about [19 mm] may be hazardous. At this point, one might have a suspicion that the cause of the problem is narrow treads rather than large nosing overhangs, but there is no evidence for this conclusion.

(A *decade after Templer, 1992, the needed convincing evidence was published; highlights are provided along with citations by Pauls and Barkow, 2013, within the ICFPP2013 proceedings.)*

> Why should large overhangs cause accidents? . . . One theory is that larger overhangs are more likely to catch the back of the heel as it pivots upward and this throws one off balance. This seems unlikely because although the heel swings up toward the nosing, it also moves horizontally away from the nosing as it pivots, so the cause of these accidents remains in question. . . . Abrupt nosing overhang projections . . . present difficulties . . . the shod foot tends to catch on the nosing. . . . Where the nosing overhang is formed by simply sloping the riser back from the nosing edge, this seems to cause no such difficulties, and these are generally permitted.
>
> **RECOMMENDATIONS:**
>
> • Abrupt nosing overhangs and any overhang greater than [17.5 mm] should not be constructed.
> • Nosings of [17.5 mm] or less seem to make steps safer.
> • Backward-sloping nosing overhangs should be used rather than abrupt nosings.

See Figure 1 (and, later in the paper, more detailed analyses based on the video from which Figure 1 is taken) in relation to Professor Templer’s comments. Figure 1 shows a mock up of a typical carpeted home stair in Canada, used by the author with US size 11.5 shoes, 310 mm in overall length, with the ball of the foot located about 220 mm in front of the back of the shoe heel. The action depicted is the lift off of the foot initiating its move to a lower tread. As shown below, the back of the shoe moves in a near-circular arc with its radius the heel-to-ball distance.

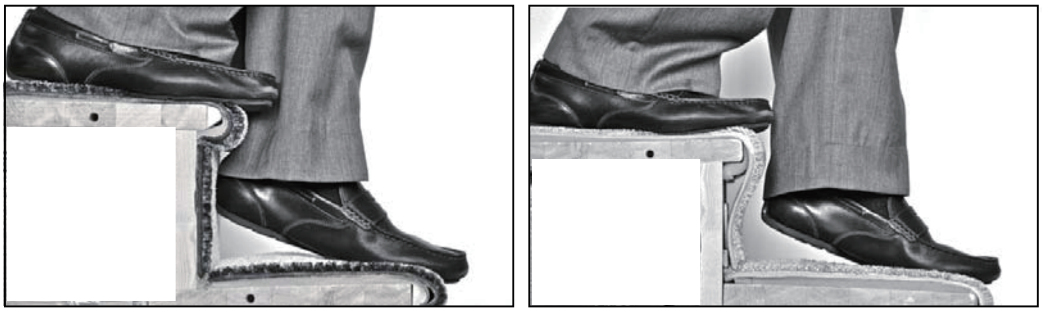
(a) (b) (c)

Figure 1. Lift off portion of descent down home stair mock up shown photographically in (a) and (b) with frame-by-frame analysis of complete use of this step shown in (c)

Significantly, while the heel started almost in contact with the base of the carpet-covered closed riser (a), there is clearly adequate clearance—by about 22 mm at closest approach (b), with about twice this clearance effectively available because a brush of the heel on the nosing carpet pile would likely have trivial consequences, i.e., not a trip or, as Templer describes it, "to catch the back of the heel as it pivots upward."

The analysis of the video shown in Figure 2(c), covers 4 seconds for both touch down and lift off (with respectively, solid-line, two-segment indications and broken-line, one-segment indications showing shoe position for each frame, at 1/24-sec intervals). It is provided here mainly to preview Figures 5 plus 6 and related analysis plus discussion.

Figure 2 shows two of the mock ups utilized by the author, illustrating (a) an undesirable, "abrupt nosing overhang," the same Canadian home-type used in all other Figures in this paper, and (b) a public stair example complying with Templer's recommendations, but only because the carpet installation is intended to represent what is called the "waterfall technique"—hiding the lip.



(a) (b)

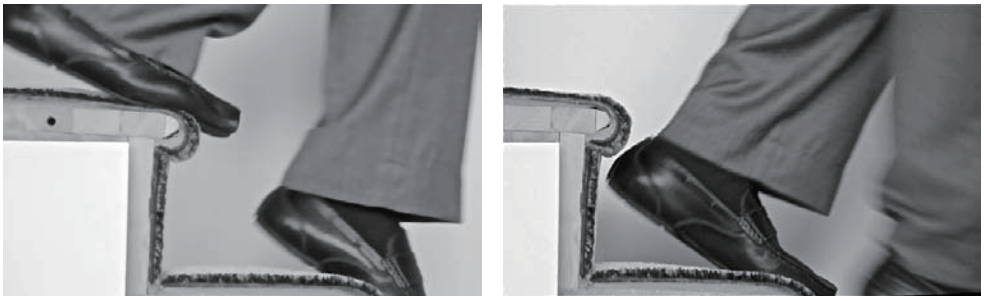
Figure 2. Mockups of (a) typical Canadian home stair and (b) typical public stair, both carpeted but with different carpet treatments that would meet typical code requirements prohibiting abrupt lips of projecting nosings, but only on public stairs

Rise-run dimensions of the two stairs are, respectively, 200 by 210 mm and 180 by 280 mm. Nosing projections in each case are, respectively, 30 mm and 25 mm, within the maximum projection limits of US and Canadian model buildings codes (with US-based "International Codes" codes using 32 mm; NFPA codes using 38 mm; and Canadian codes not yet settled on limits). The UK standard, BS5395-1:2009, limits nosing projection, with closed risers, to 25 mm. An objective of this paper is to re-open the deliberations, for such codes and standards, about the evidential base for such projection limits, in particular to assess, one, if the benefits of larger projections outweigh their dangers—*and, two, what specifically are the benefits and the dangers.*

The stairs depicted in this paper have (non-recommended) resilient underlay (partially collapsed here, representing wear and tear) which contributes to *effective* tread run dimensions of such carpeted stairs being 25 mm—or more with the passage of time—less than the minimum run dimensions permitted by codes. This can be seen, especially in Figure 2(a), with the user's foot only having effective support from the underlying wood tread about 50 mm back from the face of the carpet at the nosing (leading edge of the tread).

A central question, raised in the Templer (1992) quote, above, is the extent to which projecting nosings effectively compensate for short tread runs. Figure 2(a) illustrates multiple defects including inadequate run dimension, faulty carpet installation (and maintenance), the tripping lip below the nosing, and the fact that carpet pile attached to the riser adds to the likelihood of serious heel scuffs. Heel scuffs can lock the back of the shoe in an awkward position, shown in Figure 2(a), that might contribute to fall occurrence—as depicted in Figure 3(b). Descending stair users experiencing such serious heel scuffs have the option of twisting their feet to the side—*a common adaptation* (with "crab-like gait" being an extreme extent of such twisting). But they might also compensate by placing their feet more forward on the tread. This significantly increases the risk of an overstepping misstep and fall such as depicted in Figure 3(a) where the weight-bearing, lead foot pivots over the nosing and drops to the tread below (in what is recalled as a "slip," even though slipping is secondary to the overstep).

Both types of misstep could trigger a desperate attempt to mitigate the awkward or lost support of the lead foot, perhaps by thrusting the trailing foot forward to regain postural support with body center of mass located, horizontally, *between* the two feet positions (base of support).



(a) (b)

Figure 3. Missteps—an overstep in (a) and a heel scuff half way down the riser in (b) —leading to loss of reliable foot support, and a fall, on a short-run home stair

It is unlikely that laboratories could ethically replicate the conditions of the stair shown in Figure 4, a stair carrying a near-record flow (peaking at 1.47 persons/second over its 1220 mm, wall-to-wall width) in an evacuation drill held in 1971 in Ottawa, Canada (Pauls, 1980). Given the two flights' length and steepness—*41 degrees, with 197 mm step rise and 229 mm run*, handrail use (as documented in a video analysis) was very high at about 85 percent. Only some years after this event did the author realize, from the photograph in Figure 4, that the building occupants in that drill and in other uses of the stair had a relatively dangerous descent.

The stair risers have hundreds of scuff marks from heel scuffs, indeed the largest collection of heel scuffs in the author's extensive library of photographs. Varying recourse to twisting and/or repositioning ones feet more forward on the step appears to have produced the heel scuff records shown in Figure 4. The first risers below each of the two landings (top and intermediate) show the greatest occurrence of heel scuffs. With the adaptations just described, heel scuff occurence decreases over the flight descent, then increases again near the base of the flight. Such fascinating behaviour warrants further study beyond the introductory treatment possible in this short paper.

Figure 4. Hundreds of marks on stair risers due to heel scuffs, some of which occurred during descent in a high-flow evacuation drill in 1971.

Motion analysis of foot-stair interactions during stair descent.

Methods should be developed to facilitate detailed field documentation but, generally, such documentation is fraught with ethical and logistical challenges. In the interim—which will perhaps last forever—there is value in understanding descent dynamics at the individual step scale, as mocked up by the author for this paper (although he has used the mock up for years as a demonstration device in educational programs on ergonomics of stairway usability and safety). As may be discerned in even the small Figures possible for this report, the mock up has signs of wear and tear, especially due to dynamic loads during actual use for the video-recorded, misstep simulations. For example, in addition to collapsed foam underlay, the lower nosing piece became partly dislodged in later tests.

Furthermore, as already noted, only some dated, video-based techniques were used for motion capture, not the sophisticated systems now available in human movement laboratories. But, sometimes more important than the technology and availability of statistically significant samples, is the curiousity driving the inquiry.

For example, in the course of this work, questions arose about how one's gait on stairs can apparently be so well tuned to interactions of the feet with nosings, closed risers and carpeted surfaces as a function of run, rise and other dimensions. Rather than providing answers, Figure 5(a) and (b) may spur new questions that might, someday, be turned into research projects and subsequent changes to standards, codes—even design, construction and maintenance practices.

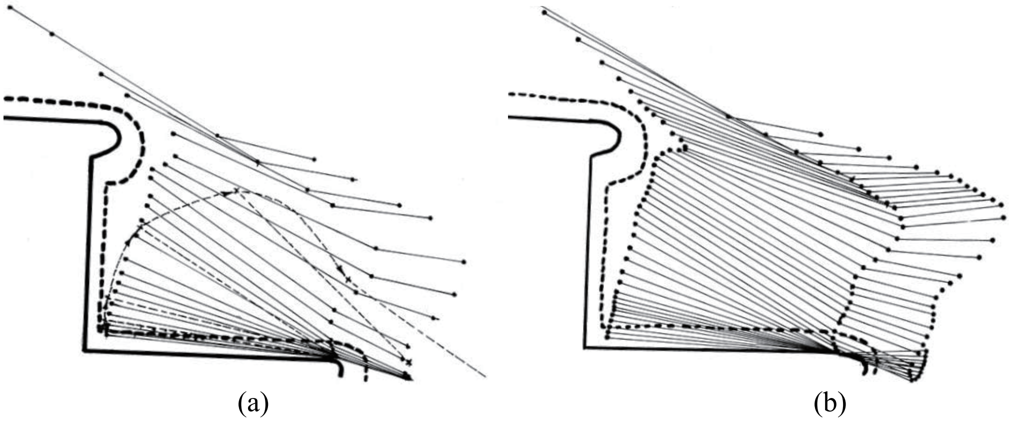


Figure 5. Analyses, from video, of two descents of a mocked up home stair, both showing interactions of step geometry and descent gait of one shod foot, with back of shoe heel, ball of the foot and front of the shoe sole indicated in two-segment lines each 1/24 second apart

The stair has easily compressed pile carpet and foam underpad (indicated by thicker, broken lines) installed above the wood construction (indicated by thicker, solid lines). Nosing projection is 30 mm. One might ask, with a closest approach distance in a 10 to 20 mm range, how does ones shod foot optimize its descent trajectory to maximize eventual footing on the tread below. Figure 5(a) includes a trace indicated with arrows, based on about 1/5 second of movement by the foot, leaving the tread with, significantly, the back of the heel moving on a circular arc with a radius of heel-to-ball-of-foot length. That this trajectory is roughly circular, in the region where the heel could get caught under the projecting nosing lip, indicates there is a relatively large margin of safety. Closest approach was about 45 mm in this particular instance and was 21 mm in another where the circular arc was even more pronounced (included in Figure 6 as part of concluding remarks). Notably, the instance of closer approach (in Figure 6) had a heel speed of about 435 mm/sec. contrasting with about 1,200 mm/sec in Figure 5(a) suggesting a more deliberate gait might be associated with a smaller clearance—*a hypothesis to test.*

Figure 5, generally, depicts a wide range of speeds of the back of the heel. In Figure 5(a) the descent speed of the back of the heel was about 250 mm/sec. and in Figure 5(b) about 150 mm/sec, in both cases for the portion of the descent below the nosing. Relative speeds are easily assessed qualitatively by visually noting the spacing between the two-segment lines representing the shoe length. Moreover, even though the gait differed noticeably in Figure 5(a) and 5(b), maximum shoe angles were, within a degree—in the 33-degree to 34-degree range.

Closing comments and a potentially provocative recommendation

Modern methods of motion capture can provide much finer-grained data and output displays—all delivered much faster and based on larger samples. However, output speed plus richness of data are not always related directly to insights gained. Even with the relatively dated, limited methods employed here, there are potential insights aplenty and data are adequate for many purposes, not all of which can be described within the confines of this paper.

Figure 6 was mentioned in a prior section in the discussion about circular arcs of trajectories for the back of the heel during lift off from the tread. Its trajectory data provide a good example.

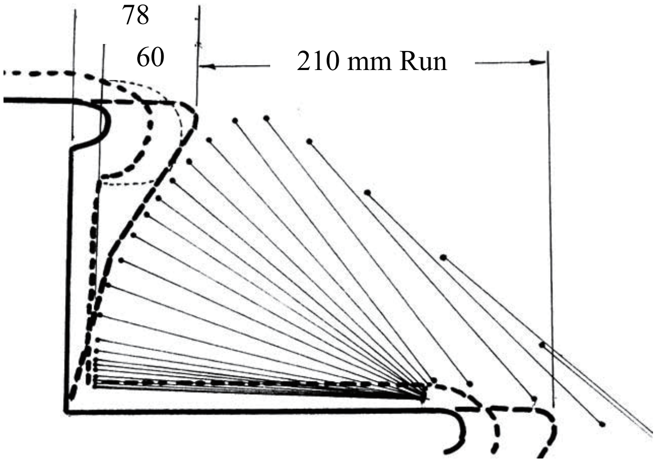


Figure 6. Analysis of foot pivot on lift off from a home stair tread as a basis for a redesign of the interface of the nosing and closed riser, preferably with a compound back slope

Turning to the potentially provocative recommendation, as hinted at the beginning of this paper, Professor Templer might have been too cautious in recommending that maximum nosing projection be 17.5 mm. My hypothesis, subject to further study (by others, I hope) is that, as depicted in Figure 6, there could be an appropriately shaped nosing projection, with no carpet cover—*and with no lip either in its junction with the rest of the tread or underneath it.* Integrated with the nosing would be closed-riser back slope(s) complying with current accessibility standards based on a 30-degree slope limit for the closed riser, relative to vertical.

While this is subject to future careful study, standards and codes could eventually be revised to permit—*potentially useful*—nosing projections, effectively larger—perhaps as much as about 60 mm to 78 mm in horizontal dimension. In theory, there is much room for compromise here with the current small limits. Furthermore, such nosing-and-closed-riser assemblies could be manufactured to facilitate retrofitting existing steep stairs—without tearing out the current structure to alter pitch—to improve usability and safety. New stairs should have reduced pitch.

With those remarks, I turn the task—including detailed research—over to others. *Be open to the possibilities and go where the data plus painstaking analysis lead.*

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