Use of 3D laser scanning stairway geometry data to better understand the risk of falls and enable improved stair regulations

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Abstract: Since overstepping is the principal cause of stairway falls, which are the leading cause of environmentally induced injury, the needs of stair users should be reflected in building codes, and the enforcement of appropriate regulations. While some codes provide greater safety, most could provide better guidance. Regulators need to determine appropriate maintenance requirements and should use mandatory reporting requirements to obtain relevant data on the dimensional geometry of a stairway when injurious accidents occur. 3D laser scanning enables comparison with BIM models during construction and offers the best means of determining the as built and existing condition of stairways, either identifying deviations or confirming code compliance. 3D point cloud data will assist expert witnesses in that such precise independent measurements are ideal for common use.

Where stairs have an inconsistent geometry, some step nosings will be in unexpected spatial locations. While short goings are known to be dangerous, the risks associated with high and low rises needs to be determined, and also the risks associated with multiple geometric deviations and/or nonconformities. It is anticipated that researchers should be able to use existing technology and techniques to determine the risks of various missteps occurring on inconsistent stairways. While much work would be required, such an investment should progressively reduce the cost of the injury burden.

Since slipping is a relatively small cause of stairway falls; slip resistance can rapidly decrease due to wear; and slip resistance cannot be reliably measured in situ on the critical part of stair nosings; it would be foolish to rely on high levels of slip resistance to significantly improve stairway safety.

Practitioner Summary: Building inspectors and expert witnesses may have to initially rely upon the assistance of proficient surveyors in making sufficiently accurate measurements and for data analysis. Conventions need to be established with respect to the data analysis, particularly the derivations of measurements and the defining of defects. Stairway researchers need to determine foot trajectory and placement strategies and motions for individuals as a function of anthropometry and stairway geometry, as well as for various populations. The iterative determination of foot clearances needs to be made to enable the determination of various types of missteps from oversteps and the gait perturbations caused by unintended contacts. The risk of falls needs to be determined from the perspective of individual unexpected variances and as a consequence of a series of variances. Regulators should gather detailed mandatory reporting data from injurious stairway falls and work with stair safety experts to enable the productive development of improved codes and better guidance.

Keywords: 3D laser scanning, stairway geometry, oversteps, missteps, falls

1. Introduction

A sister paper (Bowman \textit{et al}, 2015) discusses how building codes impose various limits on the rise and going dimensions on stairs, how stair geometry has typically been measured, and how 3D laser scanning offers a means of generating cloud point data so that any element of stair geometry can be more accurately determined using software. Eyre \textit{et al} (2015) have discussed laser scanning as an emerging technique to complement or replace traditional approaches of investigating stair accidents, where laser scanners can provide data in the form of a virtual 3D environment that can be used to reconstruct the stair and explain an event and its contributing factors.
While several technical comments could be made with respect to the field method Eyre et al (2015) adopted, considering the laser scanner used, as well as their method of point cloud alignment and data analysis, the paper still provides some useful introductory information. Novice users are urged to seek expert assistance before initiating accident investigations as it is essential to get the right combination of elements in order to produce impeccable results of sufficient accuracy.

Since such sophisticated 3D laser scanning procedures generate vast bodies of data, investigators need to reach consensus as to how should it be analysed to determine if a stairway has been properly constructed, or remains in a safe condition. Such an exercise might be broken into two: considering initially those aspects that might be mandated (for example, the rise and going dimensions and tolerances); and then determining whether there have been any variations (due to wear and tear, remodeling, etc.) that might cause safety concerns. While Roys and Wright's (2003) algorithm provides an indication of the risk of overstepping, it would seem that insufficient research has been conducted in order to determine how stair geometry influences the risk of other missteps, particularly where there are multiple deviations. In order to improve existing stair regulations to minimise the risk of falls due to oversteps and other missteps, we need to better understand how irregular stair geometries contribute to the initiation of missteps. While much past focus has been on preventing slips, where it is easy to prescribe slip resistant nosing surfaces, one should also consider whether such a simple expedient solution is likely to be effective in preventing falls in the long term.

An NAHB report (1992) assessed the role of riser and tread dimensions in accidental falls on residential stairways, at a time of considerable controversy between proponents of the more affordable 210/230 stair geometry (maximum riser height of 210 mm; minimum going of 230 mm) and the reportedly safer 180/280 geometry. The study involved a literature review of the major works and an examination of the statistical data. This in-depth review found that the research failed to establish a consistent, statistically valid link between stair safety and stair geometry. The report not only favoured the commercial status quo, it also established a most demanding (if not financially impossible) benchmark for future research in terms of statistical controls. Nonetheless, the reviewed research established a basic subjective understanding of the causes of missteps.

Stairs are the leading consumer product associated with non-fatal injuries, with over 1.2 million falls in the USA each year and an annual society injury cost of over US$92 billion (2009 dollars) (Lawrence). MUARC Report 281 (Ozanne-Smith) reported that falls account for over 80% of deaths possibly associated with building features, and falls on stairs account for over 60% of slip, trip and fall deaths in buildings. Furthermore Australian stairway injuries had increased by 70% in the decade from 1993/4 to 2003/4. Pauls (1998) has cited the high incidence of stairway fall injuries compared to fires and motor vehicle accidents. Pauls (2011) has subsequently reported a steady increase in US stair related injuries from 1998 to 2006, where all stair injury tolls were rising faster than the overall population—not only older people. This trend coincided with the increased use of prefabricated stairs in new homes, where a systematic top-of-flight dimensional non-uniformity often occurs when prefabricated stairs are fitted: the top step will often have a different going/rise ratio than the lower steps in that flight.

Pauls (2011) has suggested that those in research and standards-setting roles once thought there was adequate understanding and control of the issues. Now, we recognize the need to recalibrate or even rebuild our (admittedly) crude models, e.g., of minimum tread depth (going) for usability and safety; minimum widths based on body size, biomechanics and pedestrian fitness; handrail graspalbility, nosing conspicuity, etc.

2. What types of stairway falls occur?

Although some home stairway accidents are due to distraction (6.1%), misjudgement (7.9%) or failing to see two riser flights of stairs (3.5%), and some are due to improperly placed or missing handrails (6.9%) and objects on stairs (3.5%), only 6.9% were attributed to wet slips, 4.6% to geometrical variations that disturbed gait. The most common missteps were clearly due to oversteps (49.5%) and caught heel on nosing (11.0%), while slipping on stairs was a relatively minor problem. This analysis, based on normalisation of the data that the NAHB Research Center (1992) extracted from Alessi et al (1978), does not seem to have captured any missteps due to catching toes on nosing strips or understeps, where the heel locks against the face of the riser. However, such detail is somewhat irrelevant: obtaining sufficient data to reliably diagnose the factors that cause stairway falls is inherently difficult. Too much unreliable falls data has been collected by busy disinterested people based on the assumptions of one or more party. People who have fallen on stairs will often be unable to provide the correct causal factors or detail of the mechanism. While any data might have been informative, we now need to generate more detailed data that enables affirmative design.
Templer (1985) and Cohen (1985) generated useful data from a study of stairway risk factors based on video tape recordings of flights of stairs with the highest frequency and severity rates for stair-related injuries. While ethics committees might not permit such a contemporary study, stair laboratory studies are needed where subjects can be safely exposed to stairways where the spatial location of individual steps can be varied in order to simulate the irregular geometries present in many real world situations.

While comprehensive statistically valid research might be regarded as being prohibitively expensive, Pauls has stated that if stairway safety research in the USA had financial support on the order of a million dollars annually — much more than then the case — Injury costs would be five orders of magnitude (a factor of 100,000) greater than the cost of relevant research.

Studies of overground walking have revealed that pedestrians do not maintain a very steady speed, and there can be considerable variation in foot placement and step length. Minimum Toe Clearance (MTC) is a critical event close to mid-swing in the walking gait cycle, when foot-ground clearance is minimal (1–2 cm).

Best and Begg (2008) developed a statistical modelling technique for predicting the risk of an individual tripping on an unseen obstacle, by determining the variability in minimum toe clearance (MTC) data during treadmill walking and estimating the probability of the toe contacting an obstacle of various heights.

Fischer et al (2009) looked at the biomechanics of heel strike during level walking, where the flight path angle of the heel in the heel strike phase is critical. During heel strike, a movement and horizontal force Fx can be applied to the floor towards or opposite of the walking direction, but only when a positive force is applied to the floor (in the walking direction) can the heel slip. They found that at slow walking speeds, in 83% of walks the trajectory was negative, but as the walking speed increased the trajectory became positive. There do not appear to be any published studies of how stair descent foot trajectory varies as a function of the type and extent of single and multiple stair geometry variations.

While stair ascent and descent is more physically demanding than overground walking, the microscopic details of stair gait (particularly foot placement and the clearances between various step and foot positions) can be determined. Computer-based vision techniques can be used to automatically detect and track the feet of pedestrians during stair descent, to determine how foot trajectories are modified to accommodate various stair geometries. When applied to stairways with an individual irregularity, the dynamic gait profiles might be used to determine the probability of an overstep or other types of missteps. Where the stairway has multiple unexpected irregularities, it should be possible to determine which combination and sequence of rise/tread deviations leads to the most hazardous situations.

3. The risk of overstepping

In 2006, the Australian Building Codes Board (ABCB) commissioned a study at the Monash University Accident Research Centre (MUARC) to identify and prioritise the incidence, frequency or severity of slips, trips and falls in relation to the design and construction of buildings. Although MUARC report 281 (Ozanne-Smith, 2008) did not identify overstepping as the principal form of misstep, it did categorize the wide range of stair riser/going measurements allowed by the Building Code of Australia (BCA) as a hazardous building condition. It recommended a riser/going combination of approximately 178/280 mm, where particular attention should be given to narrowing the lower acceptable end range of goings, as up to 80% of stair and step injuries had been shown in the international literature and the national data to occur during descent and insufficiently narrow goings were a major cause of missteps during descent. A minimum going of 280 mm was identified as the minimum tread depth in the ANSI A137.1 accessibility standards.

Roys and Wright (2003) developed an algorithm for the risk of falling based on the dimensions of goings and deviations from these dimensions: the critical risk relates to overstepping the nosing on short goings. The benefits of longer goings on improving safety are again indicated in a sister publication (Bowman et al, 2015), which also gives the minimum permitted goings in Australia and the UK.

Bowman (2013) discussed how the proposed increase in the minimum going from 250 to 280 mm in the BCA should theoretically reduce the incidence of large oversteps by 94%. However, the proposal was dismissed on a cost benefit analysis, where the (unexplained) assumed effectiveness of the change was only 30%. Given the data on the incidence and cost of falls on stairs, any measure that might prevent 30% of falls would seem worthwhile, and would justify the cost of undertaking a rigorous analysis. The dismissal of the proposal was welcomed by builders seeking to minimise the footprint of stairways for economic reasons.

The Roys and Wright algorithm is based on stairs with consistent rises. However, if the rise is deeper or shallower than expected, this will have some influence on foot placement depending largely on the foot
trajectory adopted for the perceived regular stair geometry. The influence of the going may be more critical for secure foot place than the rise with respect to overstepping, but there is as yet no algorithm to determine the risk of overstepping (or other missteps) due to unexpected rise variations.

The measurement of the stair geometry is unambiguously depicted in the Australian and Singapore Building Codes, where all the treads are depicted as level. Although the BCA withdrew its guidance as to the acceptable deviations in tolerances between risers or goings on 30 December 2000, the previous values of 5 mm variation in both the riser height and tread/going dimension are still used in the New Zealand Building Code and as Australian de facto tolerances. A variation of 15 mm was permitted in the first and last riser heights, recognising that changes in adjacent floor covering specifications effect finished stair dimensions. Such tolerances could also be applied where atmospheric moisture changes caused movement of materials (i.e. cupping of timber stair treads) but not to allow for poor construction practice.

While the Singapore Code requires that the risers and treads within each flight be of uniform height and size, a note states that a 5 mm tolerance between consecutive steps is acceptable. This is presumably intended to indicate that a 6 mm variation is unacceptable. Although it fails to indicate whether a progressive small decrease in each going in a 14-step flight (say from 300 to the 275 mm minimum tread width) would be acceptable or not, a 15 mm difference certainly deviates from uniformity, whereas a 10 mm difference between successive goings of 280, 285, 280, 275 and 280 mm might be more acceptable. Builders, falls experts and trial judges would all benefit from clearer guidance, and particularly the detail of the basis on which such codes and national standards are based.

Assuming that a stairway is built with a 180/280 geometry, there could presumably be an acceptable 10 mm difference between successive rises of 180, 175, 180, 185 and 180 mm. In fact, if one plots a consistent 180/280 geometry, one should recognise that the next step might be 5 mm short or long, as well as possibly 5 mm high or shallow. Thus a step with the nominal geometry might separate a step that has a going 5 mm longer and a rise 5 mm higher from a step that has a 5 mm shorter going and a rise that is 5 mm shallow. Such variability might be accepted in some countries, be incorrect in others, and be undefined in the remainder. Since there is a fundamental need for secure initial foot placement, the risk (of overstepping) obviously becomes greater with shorter average going lengths. However, to what extent does the relative position of the nosing contribute to other common types of missteps such falls during descent and ascent? One can certainly hypothesise with respect to each, where the particular role of individual going and rise variations are likely to differ in relevance. The significance of any deduction is likely to depend on the characteristics of the individual, particularly their foot size and their elected strategy for negotiating the stair.

Does the person descending have a large foot so that his normal gait requires that he takes his downward pointing foot over the nosing before moving it backward so that he can place his forefoot just behind the nosing? Does the foot have to be considerably turned out so that the heel can be lowered onto the step (beneath any overhanging nosing) without striking the face of the riser? Is the trajectory of the foot consistently forward such that a deeper riser increases the risk of overstepping?

There should theoretically be a risk of a particular type of misstep occurring for each individual on every step they take and each stair they use. If there is a particular irregularity in a stairway, this might increase the risk of one type of misstep for some and a different type of misstep for others. Calculating the risk that such an irregularity represents requires a consideration of the probability of each type of misstep for a given population. The risk may vary significantly for a frail elderly population, a team of professional basketball players and an injured team member. If the data required to calculate such probabilities seems a daunting research prospect, perhaps the complications will only really start to arise when we have to consider how the presence of specific irregularities (that may initially disturb gait and balance) have on the occurrence of further irregularities, where these might be similar or completely different.

A greater understanding of how stair irregularities cause injurious and fatal missteps might lead to new code requirements based on safety (rather than assumptions about achievable standards of workmanship). The availability of 3D laser scanning facilitates the impartial policing of compliance with such criteria and should lead to safer new stairs and a considerable reduction in the incidence of stairway falls and deaths.

4. Stair nosings and the risk of slipping

Although MUARC Report 281 did not make any recommendations about the slip resistance of stairway surfaces, the ABCB quantified the BCA requirements for non-slip stairway surfaces from 1 May 2014. The residential and commercial building codes require that treads have a finish or a strip near the edge of the
nosings with a slip-resistance classification in accordance with AS 4586 of Class P3 or Class R10 (when dry); and Class P4 or Class R11 (when wet). The informative purpose of these amendments (to provide industry with certainty and clarity on the level of slip resistance that needs to be achieved) is laudable. However, an explanation as to why so much slip resistance is now required (compared to that available in the built infrastructure) would have been far more useful. The requirements would seem to have been based on Standards Australia Handbook 197 (HB 197) recommendations (Bowman, 1999) which were most demanding for residential use given that the recommendations also covered industrial applications.

Most slip resistant surfaces lose some slip resistance with wear, such that any requirement for new surfaces might be considered irrelevant to existing surfaces. The HB 197 recommendations were made on this basis, even if this was not stated. The extent to which such slip resistance must be retained is apparently a matter for the individual State regulatory authorities and the decision as to whether there should be any requirement (or what it will be) may be devolved to relevant building surveyors (of indeterminate slip resistance or stairway safety expertise). Figure 1 might serve as a reminder that any new requirements will not apply to the existing infrastructure; similarly polished concrete nosings where it has been assumed that any cast recessed or protruding strips (that are set back from the nosing) will fulfil any non-slip requirements.

![Figure 1](image)

Figure 1  Worn proprietary nosings on steps with 300 mm goings, in a stairway entrance (that is open to the weather but lacks handrails) to an underground Melbourne railway station. The nosing provides information about prominent paths of travel and the futility of relying on slip resistance as a panacea for preventing missteps. Such wear zones are also a function of the going length, where greater wear would have occurred on the critical part of the nosing if the going was shorter.

Some slips on stairs might be considered to be due to partial overstepping facilitated by a lack of either dry or wet slip resistance at or just before the nosing. The critical issue in overstepping is the control of the going size and the dimensional consistency. Precise location of the tread edge requires reliable cues to its visual detection prior to stepping down. The visibility of contaminants is also critical to preventing slips. Wet slips will certainly occur on external stairways, and may also occur internally where wet shoes are worn, or where parts of stairs become wet. Dry slips may also occur in the presence of dust and other dry contaminants. Slips might also occur where stockinged feet encounter dry wax polished timber nosings.

The slip resistance of the nosing might intuitively seem to influence whether or not a slip occurs when overstepping occurs. However, when a large overstep occurs, as defined by Roys and Wright, the metatarsal heads of a healthy foot have already gone past the nosing so that contact is being made with the arch of the foot that lacks an ability to provide a muscular reaction. A sufficient part of a stable shoe must be in contact with the nosing or the step in order for the weight of the body to be transferred from the ball of the foot to the whole foot as it is lowered to the surface of the step.

Many codes fail to define what the nosing is. Many proprietary nosings have metal or plastic surfaces at the critical rounded part of the nosing where slip resistance should be measured. Unfortunately many slip resistance test methods do not allow measurements to be made at this location, and nearby measurements may include parts of the underlying step surface. Measurements may be made on adjacent areas assuming identical slip resistance, but step surfaces do not wear evenly: greater wear may occur on nosings, particularly with short goings, and at a faster rate. Stair safety regulations predicated on the in-situ slip resistance of nosings seem destined to fail. There is an obvious need to reconsider what measurements should be made, how the results might be used effectively, and what is required to enable useful data.

Hunter (2013) developed an innovative simulated-foot-slip tribometer that applied the amount and rate of loading of a person at footfall on stair treads, as established by force platform tests, and simulated the downward rotation of the heel after forefoot contact on treads during stair descent. He found that nosing
shape, nosing texture and the extent of tread texture all contributed, to varying extents, to the slip resistance of stair treads. Three slip distances or types were identified: full slip off the tread; a partial slip halted by the heel breast; and a short partial slip beyond which there would be inadequate foot support. Analysis of slip duration, velocity and acceleration provided insight into the behaviour of the slipping foot, and had implications for balance retention and recovery, and therefore fall avoidance. The study highlighted the role of foot rotation in slips. While such invaluable insights are particularly useful, the simulated foot movements and step interactions need to be validated in experimental stair descent studies.

5. Understanding and interpreting real world stair geometry

3D laser scanning can quickly capture millions or even billions of highly accurate data points but can only capture what the operator can see. In the photorealistic perspective captured in Figure 2, multiple setups might be needed to scan around and fill in any ‘shadows’ created by objects such as the handrails. However, it may not be practical or cost-effective to conduct a complete scan on every aspect of a stairway. Once the project needs are known, laser scanning can increase the efficiency and reduce the turnaround time and labour costs on projects compared to traditional surveying. Such work can be outsourced where the surveyor can produce a rich dataset point cloud. The client can use to do all the work they want at a time of their choosing using their own computer without ever needing to send people back to the site.

However, conventions need to be established to make the most effective use of such data. While some building codes may proscribe tolerances for goings and risers, these requirements might be specific magnitudes based on average nominal or measured dimensions, a percentage of average dimensions, the differences between consecutive steps, or an indeterminate dictionary definition of ‘constant’. Since we have yet to determine the risk associated with specific deviations and a tumble of deviations, it would be sensible to use the power of the computer to provide several potential worst case scenarios before determining what appear to be the worst case scenario/s. A tumble has been coined as a collective term for multiple stairway irregularities that are likely to lead to injurious missteps.

Figure 2  Perspective view of point cloud data for a single scan showing an open riser office stairway.

At present an ‘analysis’ of stairway geometry data might identify that the mean riser for flight ‘X’ is 251 mm, but there are five goings that are less than the permitted BCA minimum going of 250 mm for public stairs including a going of 243 mm that also exceeds the maximum 5 mm tolerance that previously applied.
In such reporting the first question that a recipient will ask is how many ‘failures’ are permitted before a stairway must be rectified, and which deviations should be regarded as the most serious where remedial work was necessary. One international authority privately admitted that their documents were outdated and more evidential data was required: watch this space!! Code developments should be based on the sensible interpretation of available data, where caring guidance is provided with respect to the various implications and consequences of non-compliance.

Another ‘analysis’ might reveal that there was a systemic top of flight defect that might be addressed by retrofitting nosings, but that on flight ‘Y’ there was a serious problem with both irregular goings and rises. The going on step 4 is 9mm shorter than the previous going and the rise is 4 mm more than the maximum permitted by the standard and 10 mm greater than the following rise. This combination of conditions is likely to lead to an overstepping misstep. The conclusion might be quite correct, but we currently lack the evidential data that would enable us to define or deduce the exact level of risk.

![Figure 3](image-url)  
**Figure 3** Schematic of alternative methods to calculate the junction of the riser and the going point.

If a court was to direct that an independent surveyor should conduct a 3D laser scan of a stairway, there could still be some dispute as to how the data should be interpreted. Figure 3 shows a cross section through an internal timber stairway that has sloping treads, an overhang and a rounded nosing. When a graduated board and inclinometer are used, contact is made with a portion of the nosing that can be tricky to define. Figure 3 (a) shows a consistent method of fixing a defined point for the purposes of analysing the cloud point data. However, since some external steps have had 6 degree gradients (that cause the nosing on a 250 mm going to be 26.8 mm below the horizontal, extending a horizontal line from the intersection of the tread and the riser is not the best means of defining the relevant point. Figure 3 (b) thus provides a better means of defining the relevant point for the purposes of calculations. Some Building Codes may require level landings and steps, but the BCA allows landings to have a gradient up to 1:50 (which would assist with planning the drainage of external steps).

The use of 3D laser scanning during construction could help identify any defects from a BIM model, thus enabling timely control of defects such as systemic top-of flight irregularities or potential problems with handrails on large projects. Such discrepancies reflect flawed code requirements and/or flawed construction and inspection practices (Pauls, 2011). 3D laser scanning can also capture the existing condition during the lifecycle of a building, thus providing a basis for asset management and developing restoration strategies.

3D laser scanning can detect cupped and warped timber treads, and the depressions that are worn into stone steps over time, as well as the chunks of nosings that might be lost due to impact damage. The collection of water in depressions might represent a hazard in some stairways, while an unnoticed incomplete nosing would increase the likelihood of an overstep. While such anomalies might represent hazards, depending on their relative magnitude, they would automatically be recorded in a scan and any subsequent changes could be assessed.

Surveyors, building consultants and property managers are ultimately responsible and potentially liable for whether or not remedial actions are recommended or taken. Regulations cannot preconceive all the possible stairway deviations. However, a rigorous approach to the investigation of serious stairway falls should be adopted based on the use of 3D laser scanning.
Under the Australian Consumer Law, as a business if you are aware of a death, serious injury or illness associated with a product you supply, you must report it to the ACCC within two days (ACCC, 2010). Such mandatory reporting includes a wide range of potential suppliers, including a retailer, dealer, hirer, distributor, installer, repairer, importer, manufacturer and/or exporter of the consumer goods in question. Similarly, all participants in the supply chain for product related services linked to the goods are required to report the incident. This could result in the development of a useful resource (that might be inaccessible to the international stair safety community due to privacy provisions. However, since “serious illness or injury” means “an acute physical injury or illness requiring medical or surgical treatment by, or under the supervision of, a qualified doctor or nurse” this would logically mean that the ACCC should be receiving numerous reports of slips and falls associated with many flooring products. If such reports are actually rare, there would seem to need for discussions that would enable the intended benefits to flow from such schemes.

While much can be learned from experiments in stair studies, researchers need a greater understanding of the irregular stair geometries that are inducing missteps in order to better understand the associated risks and to propose improved code requirements and amended stair regulations. Given the global nature of the problem, how should the international community fund the necessary research given that it will require major investment? Finally, are there any incentives (or should there be penalties) to overcome the resistance of builders to public good changes?

References


