July 2023

CPSC Staff[1] Statement on Arizona State University (ASU) report "Factors influencing slip/fall risk while entering and exiting bathing surfaces."

The voluntary standard ASTM F462 *Standard Consumer Safety Specification for Slip-Resistant Bathing Facilities* was withdrawn by ASTM in 2016. To support the work of CPSC staff in this area and the ASTM Subcommittee's consideration of a replacement standard, CPSC awarded contract 61320621P0035 to Arizona State University (ASU) to perform three tasks:

1) Conduct literature review of existing standards and studies and determine appropriate tribology method to evaluate bathing surfaces. (ASU subcontracted this task to Forcon International)
2) Develop test surfaces for tribometer (instrument that measures friction and wear) measurement and human slip research to evaluate slip-resistance on bathing surfaces. (ASU subcontracted this task to Forcon International)
3) Conduct human research study to evaluate slip/fall on test surfaces that were developed and measured in Task 2, with focus on older populations.

The report titled, "Factors influencing slip/fall risk while entering and exiting bathing surfaces," presents the results of work by ASU on Task 3. ASU conducted a study with 61 recruited participants who entered and exited four types of simulated bathtub/shower floors under wet and dry conditions. Results indicate that entering and exiting a bathtub/shower represent a significant slip/fall risk as measured by friction demand and slip distance, especially for older adults. Older adults adopt more conservative strategies during obstacle crossing, and age-related differences in whole-body and segmental control during obstacle crossing may place older adults at greater risk of imbalance during the transition from dry to wet floor surfaces. In general, the pendulum test value (PTV)[2] of the bath surface and human slip responses correlated; albeit nonlinearly.

This work will assist CPSC staff as they continue to work to improve the safety of bathing surfaces, including working with the ASTM F15.03 Subcommittee on Bathtub and Shower Structures and other interested parties.

[1] This statement was prepared by the CPSC staff, and the attached report was produced by Arizona State University for CPSC staff. The statement and report have not been reviewed or approved by, and do not necessarily represent the views of, the Commission.
[2] The Task 1 report described how the British pendulum is the appropriate method to measure friction of bath surfaces. The pendulum test swings a rubber slider across a surface and provides a pendulum test value (PTV) that represents energy dissipation.

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Factors influencing slip/fall risk while entering and exiting bathing surfaces

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Abstract

In an effort to better understand the effect of aging on bathing fall safety, a study was conducted on four types of simulated bathtub/shower floors (referred to as Reference Surfaces or RS), tested for both a dry and wetted condition with 0.1% sodium lauryl sulfate (SLS) in water as a contaminant. Sixty-one (61) young and older adults were recruited from the surrounding areas of the Phoenix metro area. The experiments were conducted at the ASU Locomotion Research Laboratory in Tempe, Arizona. All patients included in this study were generally healthy. The focus of this manuscript relates to how older adults navigate entering and exiting bath surfaces (bathtub and shower mockups). We hypothesized that age as well as the demands of entering and exiting the bathing surfaces would influence Friction Demand (μd) and slip distance (SD) thereby increasing fall risk. We also hypothesized that different types of bathtub/shower floors would perform differently, to the extent that they utilize different friction mechanisms. Results indicate that entering and exiting a bathtub/shower represent a significant slip/fall risk as measured by RCOF or Friction Demand and slip distance especially for older adults. Older adults adopt more conservative strategies during obstacle crossing, however, this strategy as measured by stepping time indicates that the transition of the whole-body center of mass (COM) was delayed resulting in increased friction demand and slip distance (i.e., slip and fall risk). Age-related differences in whole-body and segmental control during obstacle crossing may place older adults at greater risk of imbalance during the transition from dry to wet floor surfaces. Furthermore, Pendulum Test Values (PTV) associated with reference surfaces corresponded with number of slips greater than 1.5 cm. Slipping behaviors related to friction demand were ascertained without using handrails to better understand the bathing surface dynamics of the slip/fall event.

INTRODUCTION

The US Centers for Disease Control and Prevention (Stevens, Haas, and Haileyesus 2011) reported that in 2008, approximately 21.8 million individuals aged more than 15 years sustained nonfatal, unintentional bathroom injuries, resulting in significant economic losses ($67.3 billion in lifetime medical costs), with an estimated 234,094 injuries requiring emergency department visits. Importantly, injury rates increased with age and more than 80% of the nonfatal injuries were attributed to falls.

The most common locations noted were within the bathroom narratives, which included the words “bath,” “shower,” or “tub.” Additionally, the precipitating events were listed as “bathing” or “showering” or “slipping.” The highest rates were those injuries occurring in or around the tub (65.8 per 100,000), and about 37.3% of injuries were associated with getting out of or exiting the bathing surface, while only 2.2% were reported as occurring while entering the bathing surface (Stevens, Haas, and Haileyesus 2011). Recent data provided by the Consumer Product Safety Commission (2010 to 2021) regarding bathing surface accidents leading to fatalities also had similar trends – fatalities increased with increasing age (Figure 1).

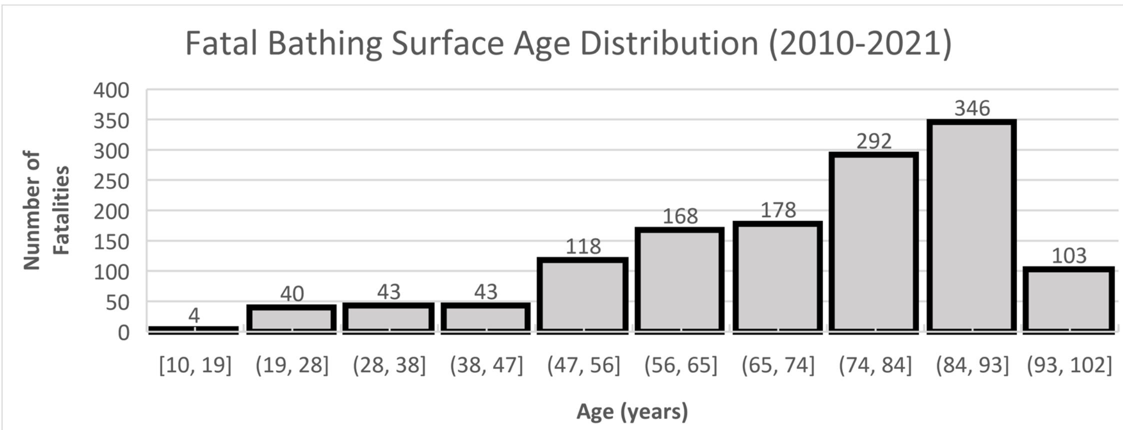


Figure 1: ***Number of Fatalities vs. Age (years) for 2010-2021 (CPSC-Provided Data).***

There may be numerous contributors to bathing surface falls including stepping mechanisms when entering and exiting a bathtub, which requires avoiding elevated obstacles and potentially slippery surfaces.

Entering and exiting a bathtub/shower requires stepping over and across an obstacle (bathtub rim heights are typically 15 – 19 inches) while transitioning between different floor surfaces. This transition may place a significant demand on the interplay between musculoskeletal and balance control systems and represent a significant slip risk as characterized by Friction Demand (μd) and slip distance. Friction demand (μd) is a ratio between horizontal and vertical ground reaction forces during the heel or toe contact phase of the stepping motion and it represents the friction required for the foot to not slip. Additionally, due to age-related declines in musculoskeletal, motor, and sensory function, bathing transfers may pose a significant risk to older adults leaving them susceptible to falls. Approximately one in seven older adults that have difficulty entering and exiting their bathtub/shower reported “getting stuck” at least once over a one-year period; furthermore, unsuccessful bathtub transfers account for more than 70% of falls in the bathroom among older adults (Aminzadeh et al. 2001; Stevens, Haas, and Haileyesus 2011). Evidence suggests that older adults adopt more conservative strategies during obstacle crossing (e.g., the height of the rim), however, it is unclear how this may influence the slip risk on bathing surfaces.

In an effort to better understand the effects of gait initiation and stepping responses or friction demand and slipping characteristics to different heights associated with bathing sources (bathtub and shower pan) and bathing surface conditions (dry and wet), a study was conducted on four types of simulated bathtub/shower floors (referred to as Reference Surfaces or RSs), tested for both a dry and wetted condition with 0.1% sodium lauryl sulfate in water as a contaminant. The work done for this study was under Contract 61320621P0035 with the U.S. Consumer Product Safety Commission. The focus of this manuscript relates to how older adults navigate entering and exiting bath surfaces (bathtub and shower mockups). We hypothesized that age as well as the demands of entering and exiting the bathing surfaces would influence Friction Demand (μd) and slip distance (SD). We also hypothesized that different types of bathtub/shower floors with different friction levels as measured by the Pendulum Test Value (PTV) will correspond with human slipping responses as measured by slip distances great than 1.5cm, both forwards – associated with initial heel contact, and backwards – associated with toe-slip while going into and out of bathing surfaces.

METHODS

Participants: The sixty-one (61) participants' information is listed in Table 1. Participants were recruited from the surrounding areas of the Phoenix metro area. The experiments were conducted at the ASU Locomotion Research Laboratory in Tempe, Arizona. All patients included in this study were generally healthy (Table 1) and the age distribution of the participants are illustrated in Figure 2.

Table 1. Participant information.

	Older		*Younger*	
	Mean	*Std Dev*	*Mean*	*Std Dev*
Number of Subject (N)	35		26	
Male (N)	12		18	
Female (N)	23		8	
Age	77.34	5.77	22	3.35
Height (cm)	166.54	7.71	171.34	16.6
Weight (kg)	78.07	19.42	73.07	10.75
BMI(kg/m^2)	28.1	5.91	23.42	6.55

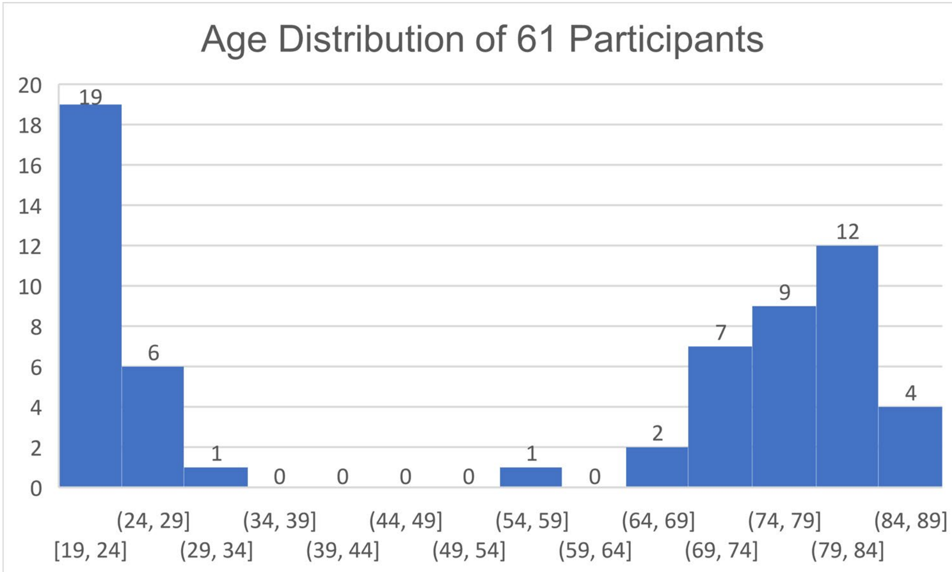


Figure 2. Distribution of test participants in each age group in this study.

Equipment: State-of-the-art motion capture systems were employed to assess kinetic and kinematic data during entering and exiting the bathing surfaces. In general, the motion-capture system consisted of: Vicon® Nexus software, 3 video cameras, and 10 Bonita cameras (Oxford Metrics, Oxford, UK) to track the kinematics of whole-body movement within the integration of kinetics. Additionally, two AMTI AccuGait-Optimized™ multi-axis force platforms were utilized to assess the ground reaction forces during the walking step with one platform mounted inside the bathing surface mockup and the other in the "floor" adjacent to the mockup. An inertial measurement unit (IMU) system was used to assess the slipping dynamics of shank motions (acceleration, magnetometer, and gyroscope data in x, y, and z directions). A bathtub/shower mockup (Figures 3A and 3B) was used in this study and was made to accept interchangeable 18-inch square RSs to be tested. Simulated "rims" for the bathtub (38cm high) and shower (8cm high) were created from foam rubber. It is of note that the elevation changes between the "bathroom floor" and the RS center were 6.4 cm for the "bathtub" configuration and 1.9 cm for the "shower" configuration (Figure 3C). Production bathtubs may have up to 10 cm elevation difference between the bathtub floor and the bathroom floor.

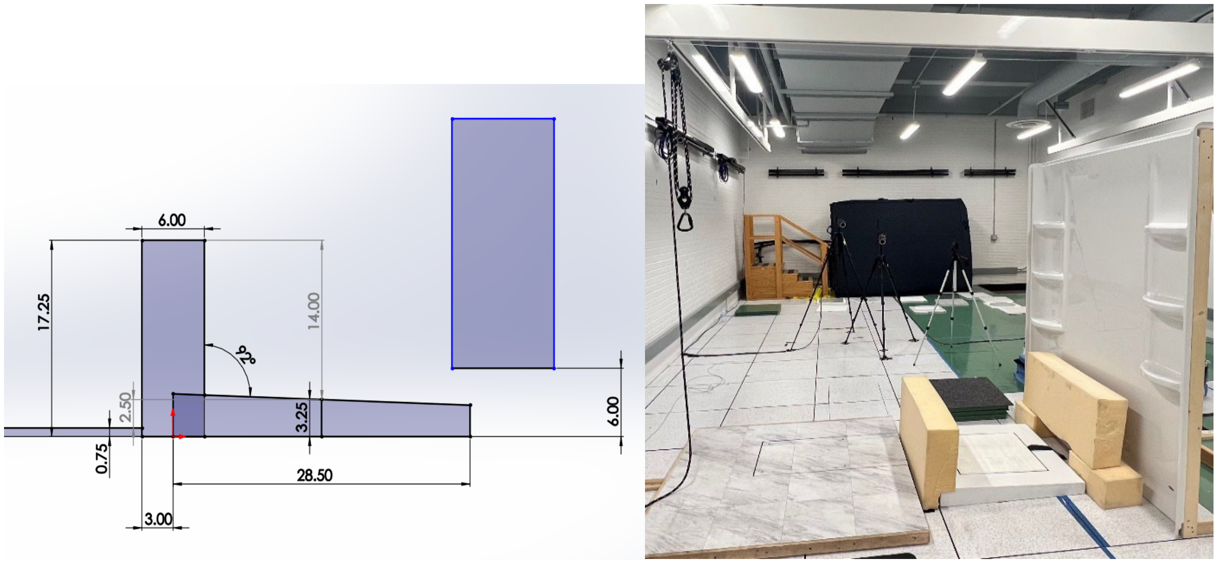


Figure 3A. Side-view showing “Bathtub” mockup used for subject testing (note: all dimensions in inches). Figure 3B. Side-view of the testing showing a participant entering and exiting the Bathtub mockup.

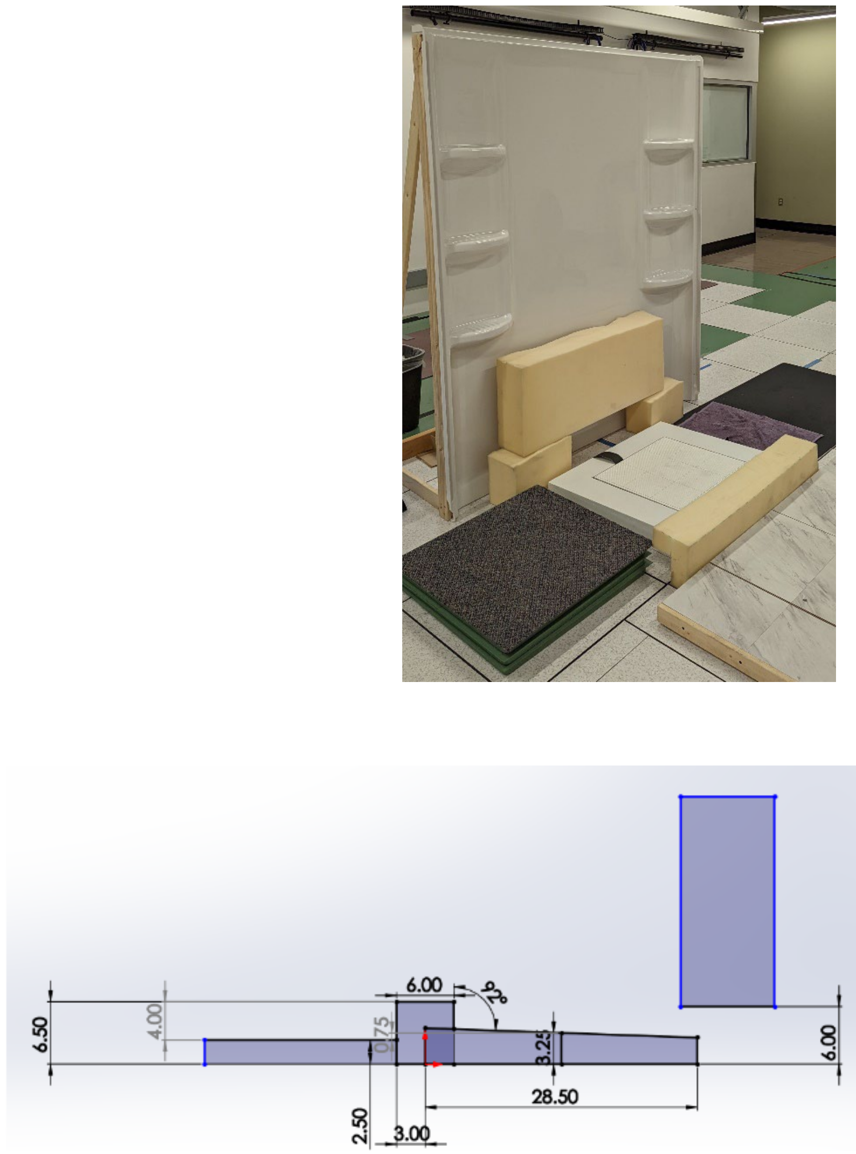


Figure 3C: Side-view showing geometry for “Shower” mockup used for participant testing (all dimensions in inches).

Reference Surfaces:

As certain designs of these Reference Surfaces (RSs) may be used in a future ASTM bathing surface friction standard, they are referred to as Reference Surfaces (RS) in this paper. The RSs were mounted at a 4% (~2.3°) slope as shown in Figures 3A and 3C to correspond to the maximum bathing surface floor slope allowed by American Society of Mechanical Engineers (ASME) A112.19.1 / Canadian Standards Association (CSA) B45.2; this represents a worst-case slope configuration for both entering (heel/toe contact) and exiting (toe-off) from the bathing surface. The friction testing for the RSs was done using a British Pendulum tribometer, using a test methodology generally based on Australian and United Kingdom Pendulum methods. RS materials included the following (Figure 4):

- **Porcelain-enameled steel**: Such bathing surface products typically use "gritty" surface roughness features (patterned or uniformly applied) to facilitate friction. These study RSs were fabricated by cutting out uniformly-gritty production bathing surface floors and then creating different patterns of friction features by polishing away selected areas of grit; the process was intended to make these RSs more slippery than the production units.
- **Embossed (vacuum-formed) sheet plastic**: Such bathing surface products typically use 3D-profiled patterned friction features embossed into otherwise-smooth glossy sheet acrylic. These study RSs were fabricated by vacuum-forming 0.5mm-1.0mm (0.02-0.04 inch) thick polyethylene terephthalate glycol (PETG) sheet atop different 3D feature patterns created with a 3D printer utilizing fused deposition modeling.
- Simulated **gelcoat/fiberglass**: Such bathing surface products typically use 3D-profiled patterned friction features molded using a composite layup of a gelcoat (colored unreinforced resin) exposed surface backed by fiberglass and polyester resin. Due to various constraints, two of the three study RSs simulated the gelcoat/fiberglass using 3D feature patterns created with a 3D printer. The patterns were printed in polylactic acid (PLA) resin, sanded, and sprayed with a 2-part epoxy bathtub refinishing coating. The remaining RS was fabricated of gelcoat with fiberglass backing.
- Simulated **mosaic tile**: Mosaic tiles are used to field-fabricate shower floors; mosaic tiles come in pre-spaced arrays of small tiles glued to a mesh backer, and they are installed by bonding and grouting the mosaics into the bottom of a shower pan. This fabrication process lacks any consistent control of individual mosaic position and orientation; such variability in an RS could complicate human testing. As such, simulated mosaic tile arrays were created by cutting different patterns of partial-depth grooves into American Wonder Porcelain "Orvieto OR01" porcelain tiles.

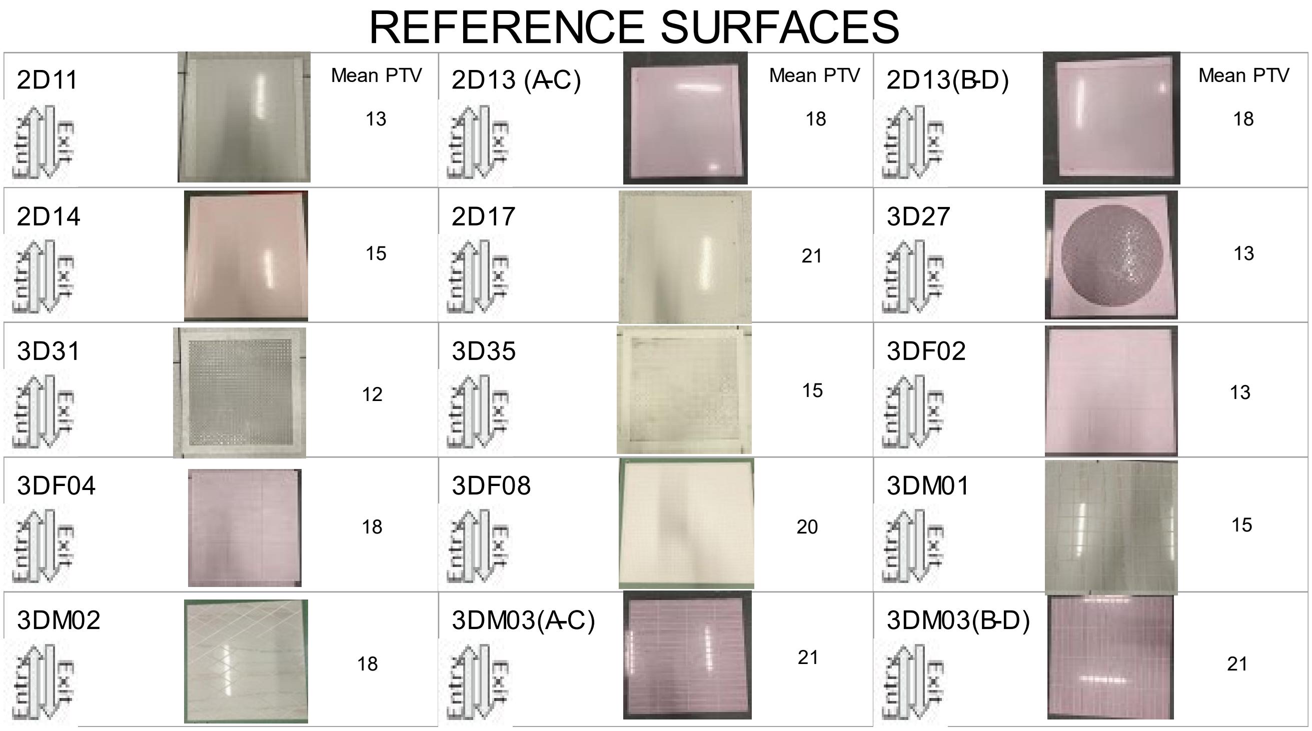


Figure 4. Reference surfaces with walking directions entering and exiting the bathing surfaces including the mean PTV – Pendulum Test Value (higher values indicate higher measured friction).

Procedure:

Subject testing was conducted barefoot for both entering and exiting each bathtub and shower mockup. Each subject enters and then exits the mockup. For entering: each subject started at least 1.5 meters from the bathing surface (bathtub or shower mockup) and at a self-selected walking pace stepped onto a “bathroom floor” that included an instrumented forceplate, and then stepped over a 8cm “shower rim” or a 38cm “bathtub rim” onto an RS mounted atop a second instrumented forceplate, and then the subject would stop. Subjects would then step onto the RS frame (not instrumented), turn around, and then step back onto the RS prior to exiting. Subjects had dry feet before beginning this test. For exiting: each subject would stand on the RS/forceplate inside the bathing surface mockup and then step over the 8cm (shower) or 38cm (bathtub) obstacle onto the “bathroom floor” forceplate, and then the subject would stop. Subjects had wet feet before beginning this test. Only dry bathing surfaces were used to assess Friction Demand (μd) characteristics, in generally non-slipping test events; friction demand characterization (using forceplate measurements) is problematic if a nontrivial slip occurs. Slip event characteristics were evaluated (on wetted RSs) based on the Lockhart et al., 2003 method, with dependent variables including slip distances and stepping time. Trials were omitted from the total sessions if participants did not step onto the RS fully (contacting the RS frame) or if their foot contacted the simulated bathing surface rim (foam material).

Data Analysis:

Independent variables were: 1] age group (younger or older adults), 2] bathing surface (bathtub or shower mockup), 3] whether the subject was entering or exiting the mockup (in or out), 4] RS condition (whether the RS was dry or wet), and 5] RS utilized (15 RSs in total were tested).

Dependent variables are listed below:

> Note: Since we are measuring slipping while stepping onto the bathing surfaces as well as getting out of the bathing surfaces, the term Heel Contact Velocity (HCV) is associated with entering the bathing surfaces. While getting out of the bathing surfaces, the last contact of the foot mostly occurs with the toes, during the toe-off phase of the gait cycle similar to heel contact during stepping. As such, Foot Velocity (FCV) was adopted in this study to eliminate any confusion. The following are the dependent measures related to going into the bathing surfaces (heel slips, Figure 5) and getting out of the bathing surfaces (toe slips, Figure 6).

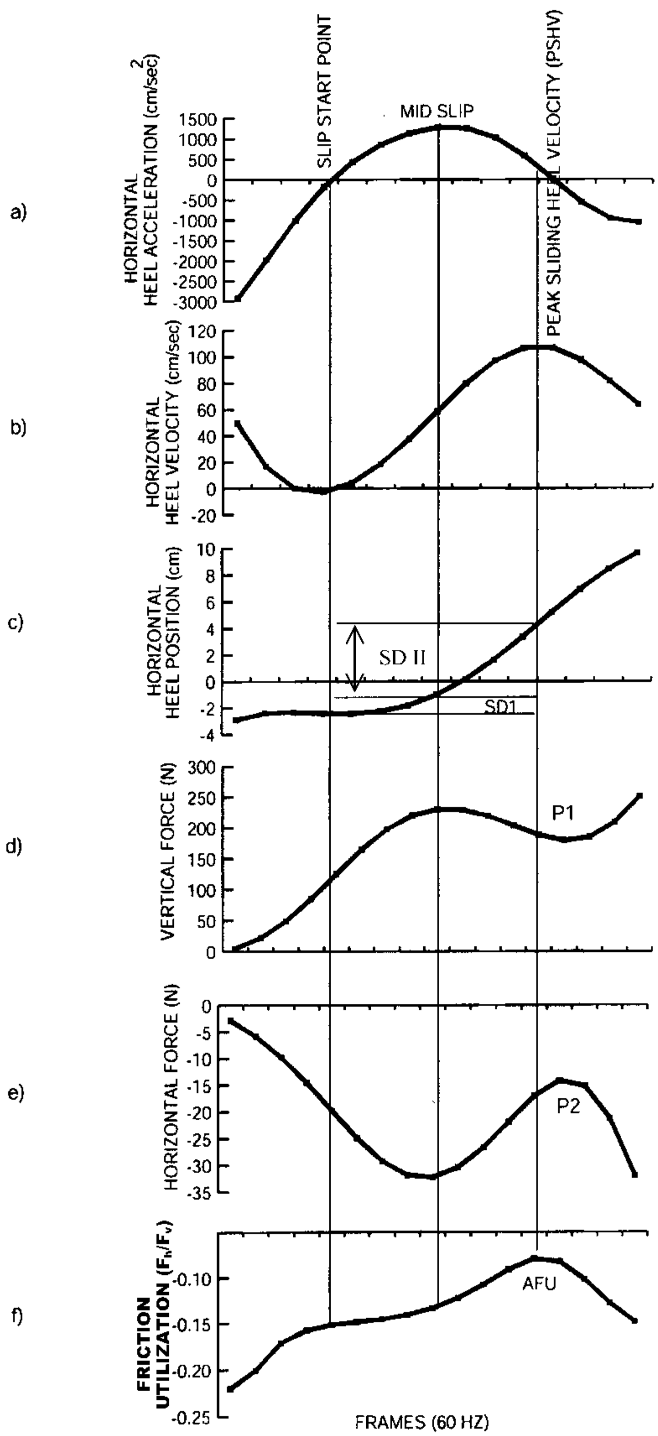
1. Initial Slip Distance (SDI) (cm): this is the resultant distance traveled by the foot once the heel or toe is sliding. SDI was measured to provide information concerning the severity of the initiation of slips. The SDI start point was defined as the point where forward acceleration of the leading heel or rearward acceleration of the trailing toes occurs and the stop point was defined as the point where peak heel/toe acceleration occurred after the slip-start point (mid-slip in figure 4a). Thus, SDI is calculated using the heel/toe coordinates between start (X1, Y1) and stop (X2, Y2) points on the RS surfaces (Figure 5c) and using the distance formula. For toe slips see Slip Initiation in Figure 6.

2. Slip Distance II (SDII) (cm): this is the distance traveled by the foot after the peak heel acceleration. It was measured to provide information concerning slip behavior once the heel or toe is sliding. The start point for SDII was defined as the SDI stop point, and the stop point for SDII (for the purpose of calculation) is the point of the first maximum of the horizontal heel velocity occurred (Peak Sliding Heel Velocity [PSHV], Figure 5 a, b and toe velocity (PSTV) Figure 6). Taken together these will be called Peak Sliding Foot Velocity (PSFV). Additionally, SDII is calculated utilizing a general distance formula.

3. Instantaneous Horizontal Heel contact or Toe off Velocity (FCV) (cm/s): The instantaneous horizontal heel/toe velocity during heel/toe contact was calculated utilizing heel/toe contact velocities in the horizontal direction at the foot displacement of 1/60 s (Dt) before and after the heel/toe contact phase of the step cycle. Here, for getting out of the bathing surfaces, the last step leaving the bathing surface is associated with toe-off – as toe-off velocity was considered to be the Foot Contact Velocity.

4. Friction Utilization/Demand: The peak required coefficient of friction (RCOF) (also known as friction utilization or friction demand) was obtained by dividing the horizontal ground reaction force by the vertical ground reaction force (Fh/Fv) after heel contact entering the bathing surfaces and during the toe-off phase of the gait cycle in exiting the bathing surfaces.

5. Stepping time: time associated with stepping while entering or exiting the mockup bath or shower– starts at toe-off and ends at heel contact.



Figures 5a - 5f. Illustration example of calculation of slip parameters (slip distance 1 (SDI), slip distance 2 (SDII), sliding heel velocity and accelerations) during slipping with ground reaction forces adopted in this analysis (Lockhart et all, 2003). This plot is only pertaining to heel slips entering the bathing surfaces.

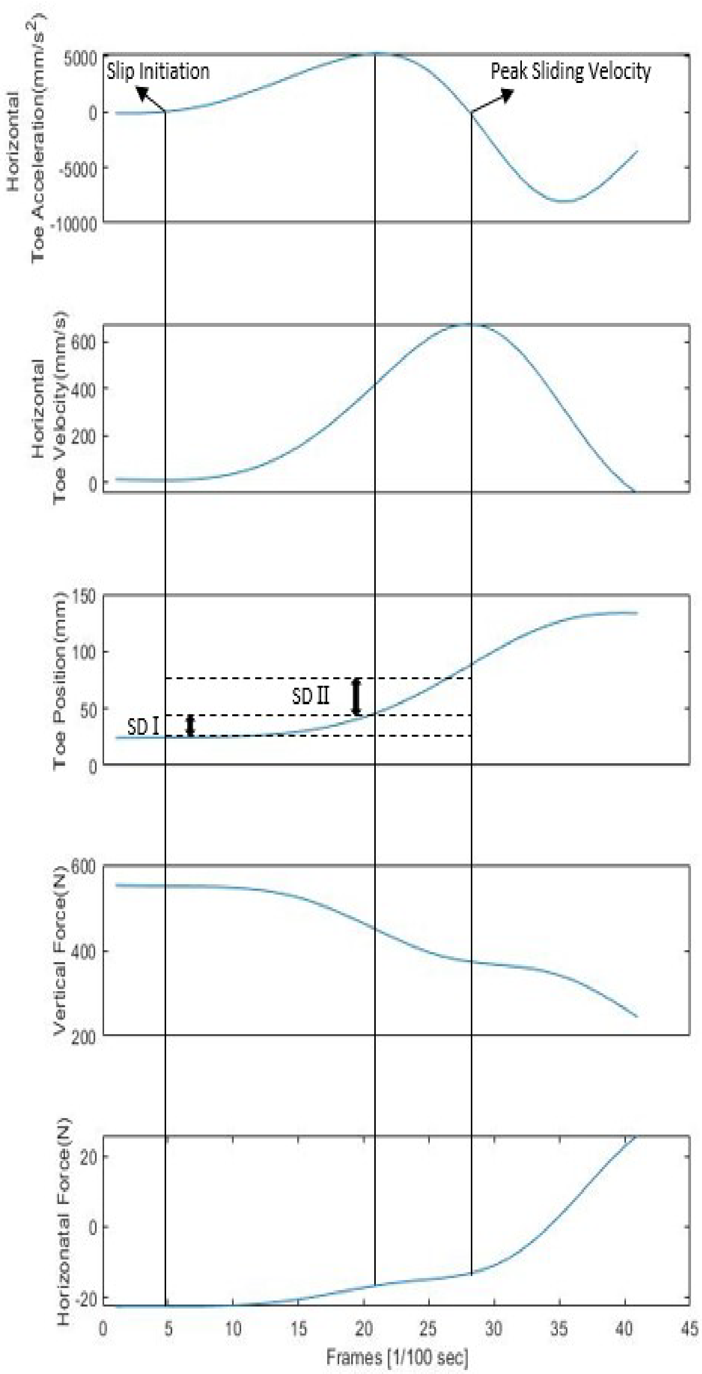


Figure 6. Illustration example of calculation of slip parameters [slip distance 1 (SDI), slip distance 2 (SDII), sliding heel velocity and accelerations] during slipping with ground reaction forces. This plot is only pertaining to toe slips exiting the bathing surfaces.

RESULTS

Dry Bathing Surfaces

The study quantified the minimum frictional performance required for dry bathing surfaces. RCOF was evaluated at the heel contact phase of the stepping foot while entering the bathing or shower area mockup and the toe-off phase of the stepping foot while exiting the mockup. Thus, we concentrate on the dry floor surfaces while entering and exiting bathing surface mockups.

In general, RCOF was significantly greater when stepping-out compared to stepping-in for both young and older adults. However, the "Age x In/out" interaction effect indicates that older adults' friction demands while stepping out of the bathing surfaces were significantly higher than their younger counterparts. This may directly attribute to the number of fatalities while stepping out of bathing surfaces for older adults.

In general, we found no significant differences between heel velocity among all participants. The older adults' stepping times were significantly longer than their younger counterparts. No significant slip distance differences were found on the dry bathing surfaces.

Table 2. Results of friction demand and stepping time going in and out of the bathing surfaces by young and older adults.

	Dry Surface				p-values		
	Older		*Younger*				
	In	*Out*	*In*	*Out*	*Age*	*In/Out*	*Age x In/out*
Required Coefficient of Friction	0.212 (0.133)	0.342 (0.202)	0.199 (0.131)	0.248 (0.140)	<.0001*	<.0001*	<.0001*
Step Time	0.7697 (0.202)	0.851 (0.203)	0.750 (0.147)	0.816 (0.170)	0.004*	<.0001*	0.3714

Wet Bathing Surfaces

The study quantified certain slipping risks associated with entering and exiting the bathing surfaces while wet (RS spray treated with 0.1% SLS/water solution prior to testing). To assess the wet bathing surface's interaction with human slip responses, we measured foot velocity at the instant of the heel contact as well as sliding heel velocity when slipping in case of entering the bathing surfaces. We also measured the velocity at the instant of the toe-off phase of the gait cycle as well as sliding toe velocity when slipping during exiting of the bathing surfaces. Results indicate that Peak Sliding Heel/Toe Velocity (PSFV) and the slip distance SDI and SDII were significantly influenced by entering and exiting the bathing surfaces as well as by interaction effects of "Age x In/Out". In general, older adults slipped faster and longer than their young counterparts, and when exiting the bath surfaces experienced faster slips and longer slip distances.

Table 3. Results of wet surface testing (SDI, SDII, PSFV and step time) during entering/exiting of the bathing surfaces by older and younger adults.

	Wet Surface				p-values		
Slip Distance I	*Younger*		*Older*				
	In	*Out*	*In*	*Out*	*Age*	*In/Out*	*Age x In/out*
Slip Distance I	18.42 (6.95)	17.64 (6.53)	26.97 (6.49)	22.07 (12.17))	<.0001*	0.0003*	0.0456*
Peak Sliding foot Velocity (PSFV)	156.171 (296.901)	355.530 (402.573)	545.764 (1029.847)	951.328 (1389.259)	0.0005*	0.0298*	0.456
Step Time	0.765 (0.196)	0.875 (0.289)	0.743 (0.160)	0.792 (0.190)	<.0001*	<.0001*	0.0058*

Effects of Pendulum Test Values (PTV) associated with different reference surfaces

The relationship between PTV and human slip responses were assessed. The investigation was associated with all RSs except for 2D17 which had a higher PTV value but inconsistent slip responses. In general, PTV and human slips percentage corresponded somewhat nonlinearly. However, we can clearly see that higher PTV was associated with less slips. Further PTV values are needed to model the human slip responses; the relationship explained 86% of variances -i.e., R^2=0.86.

Table 4. Pendulum Test Values associated with RS and corresponding slips that are more than 1.5cm.

Reference Surfaces	PTV	Slip %
(3D31)	12	10
(2D11,3D27,3DF02)	13	5
(2D14, 3D35, 3DM01)	15	3
(2D13, 2D13 (A-C), 2D13 (B-D), 3DF04, 3DM02)	18	3
(3DF08)	20	3

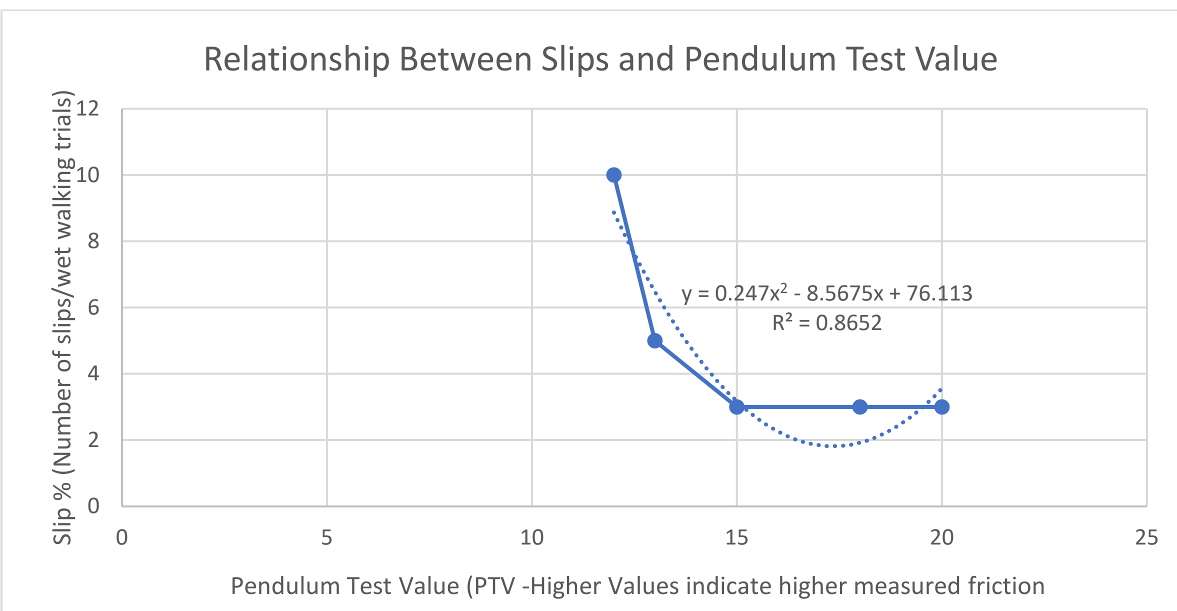


Figure 7. Illustration of the relationship between human slip responses and PTV.

DISCUSSION

The mechanics and the forces involved in slipping are important in understanding fall accidents. The forces applied by the foot to the floor when it touches the floor surface act in three directions: vertical (Fv), horizontal (Fh) in the direction of body motion, and horizontal-transverse (Ft), perpendicular to the direction of body motion. Note that by Newton's third law, the ground reaction forces exerted by the floor on the foot are equal and opposite to the forces exerted by the foot on the floor. Upon heel contact there is a resultant forward thrust component of force against the floor, and upon toe-off of the trailing foot there is a rearward thrust component against the floor. This results in anterior/posterior shearing forces (Fh) acting at the foot-toe/floor interface. Lateral-transverse force (Ft) is the result of the lateral momentum during the gait. This lateral momentum exists due to an out-toeing walking/stepping pattern. In normal-level straight-line walking, this force component can be ignored due to the relatively small transverse forces compared to the other ground reaction forces, however, during the toe-off phase of the stepping cycle while exiting the bathing surfaces, the transverse friction demand was significantly higher than when entering the bathing surfaces, and thus cannot be ignored. These differences were observed for older adults especially. In other words, older adults were demanding more friction than their younger counterparts during the toe-off phase of the stepping movement while exiting the bathing surfaces. Although it is unclear why older adults were demanding more friction while exiting the bathing surfaces than entering, compared to younger adults, it may be that trajectory control of the whole-body Center-of-Mass (COM) may have been compromised due to degraded motor control – e.g., not bending at the trunk to timely distribute more force to the stepping foot. This is indicative of stepping time delay which causes the whole-body COM to lag thus creating greater horizontal force and increasing friction demand. The key question is then, does the greater friction demand while exiting the bathing surface influence slip/fall risk?

Step Adaptations & Obstacle Avoidance During Bathtub/Shower Transfer

Evidence suggests that older adults adopt more conservative strategies during obstacle crossing, including slower anticipatory and crossing speed, shorter step length, shorter post-obstacle heel strike distance (Chien, Post, and Siu 2018), and longer pre-obstacle toe-off distance than younger adults (Begg and Sparrow 2000), Older adults also exhibit lower toe clearance compared to younger adults when compensating for an obstacle (Galna et al. 2009). In addition to reductions in hip flexor strength, limitations in hip abductor strength in older adults may explain lower vertical toe clearance compared to younger adults; reduced hip abductor strength could cause pelvic drop during stance, effectively lowering the height of the swing limb (Mcfadyen and Prince 2002). It has also been reported (Mcfadyen and Prince 2002) that older adults cross obstacles when their COM is farther forward in the swing phase of the crossing step compared to younger adults. Crossing later in the swing phase may reflect an effort to increase toe clearance above the obstacle, however, it also means that older adults have less time to recover balance in the event of contact with the obstacle or an unbalancing event. As well, the further forward in the stance phase a person is, the greater the anterior/posterior horizontal shearing forces are (acting between the foot and underfoot surface), and in turn, the greater the frictional demand. In the scenario of a marginal-friction underfoot surface, crossing the obstacle later in the stance phase can increase slip risk.

Slower crossing speed observed in older adults may reflect a cautious strategy in response to perceived risk, however taking longer to cross over the bathtub rim increases the time the participant spends having to control their COM within a narrow and moving base of support (Winter 2009). On a slippery surface in particular, this challenge could increase the risk of balance loss. King and Novak (2017) investigated age-related changes in postural control during the task of entering and exiting the bathtub. As a point of reference, they described that most individuals enter and exit a bathtub in the direction of “progression”: to approach perpendicular to the bathtub rim, such as facing the back wall of the bathtub during entry.

Older adults adopted a more cautious strategy than younger adults when stepping over the bathtub rim (marked by a reduction in the center of pressure displacement in the direction of progression); however, despite this caution, older adults displayed greater variability of the center of pressure displacement in the axis of progression, which the authors suggested may indicate poorer balance control. When stepping over the bathtub rim in this way, a balance perturbation in the perpendicular axis (parallel to the bathtub rim) would likely require a lateral step for balance recovery, especially in the absence of graspable support. In addition to the bathtub rim potentially being in the way of a stepping reaction, these laterally-directed compensatory steps are challenging and often poorly executed by older adults, which may increase the risk of an injurious lateral fall (Maki, Edmondstone, and McIlroy 2000). King and Novak’s research did not address shower-height rim obstacles.

In addition to spatiotemporal and balance-related differences with aging, obstacle crossing may also result in altered trunk kinematics for older adults. Previous studies studied the effect of age and height on movements during obstacle crossing and found that older women bend their trunk forward and tilt their upper body laterally during the swing phase of the trailing limb (Chien, Post, and Siu 2018). The authors suggested that this trunk movement could represent a compensatory strategy in response to reduced lower limb strength to accommodate crossing a high obstacle (height of obstacle relative to the height of subject). With increasing task demands, these altered trunk kinematics observed in older adults (and individuals with a disability) may have implications for fall and injury risk in the event of balance loss. The ability to arrest and counteract movement and displacement of the trunk plays a major role in avoiding a fall (Grabiner et al. 2008). This requires substantial coordination and force generation, given that the trunk accounts for approximately half of the total body mass in older adults (Jensen and Fletcher 1994). Greater displacement of the trunk, paired with reduced strength and/or age-related physiological changes to the vestibular system, may limit an older adult’s ability to generate the necessary postural responses to maintain dynamic balance in the event of destabilization. In terms of fall risk, a greater forward trunk flexion angle at the time of balance loss increases an individual’s risk of falling. While Jensen & Fletcher’s work pertained to falls on level ground, risks may be similar when an individual is entering and exiting the bathtub, during which they must negotiate changes in surface height while an underfoot surface for compensatory stepping is likely unavailable. A bathtub contains many hard surfaces on which an individual can fall, such as the faucet and bathtub rim; such surfaces may increase the risk of head injury upon impact.

Obstacle crossing places large demands on the body’s balance control systems. Successful obstacle crossing requires controlled movement of the whole-body COM within a narrow base of support (a single limb in contact with the ground) as the contralateral limb swings over the obstacle (Novak and Deshpande 2014). Crossing over a high obstacle requires greater swing limb elevation and this increases balance demands (Chou et al. 2001). It elicits large center-of-mass movement in both the sagittal and frontal planes; the COM moves in the anterior then mediolateral direction towards the center of pressure of the supporting foot (Chou et al. 2001). Large inertial forces are generated and the COM moves closer to the base of support boundaries; this further challenges balance control (Winter 2009). These gait adjustments are required during obstacle crossing to unload the leading foot and generate the vertical reaction force needed to rotate and propel the body forward about the ankle (Desforges, Tinetti, and Speechley 1989). Such gait adjustments during obstacle crossing are more pronounced in older adults and may not be as well controlled (King and Novak 2017). Novak & Deshpande (2014) suggested that age-related differences in whole-body and segmental control during obstacle crossing may place older adults at greater risk of imbalance. The authors found that older adults increase anterior-posterior trunk motion during obstacle crossing; since past work has shown that older adults also place their leading foot closer to the obstacle compared to younger adults, a strategy that shortens or reduces the anterior-posterior base of support, older adults must control larger trunk motions within a smaller base of support, and this could increase risk of imbalance (Novak and Deshpande 2014). Further, age-related physiological changes such as declines in skeletal muscle strength may limit an older adult's capacity to generate muscle force and maintain dynamic stability during obstacle crossing, particularly in the event of a destabilization (Marigold and Patla 2002). Older adults use a greater percentage of their neuromuscular capacity and strength to successfully cross obstacles compared to younger adults, characterized by greater activity in the lower extremity muscles (Hahn, Lee, and Chou 2005). This means that for safer obstacle crossing aimed at preventing them from falling, older adults have greater neuromuscular demands than younger adults for the same task. These increased demands make obstacle crossing more challenging for older adults and may increase the risk of slips during a time-intensive task such as bathing; fall risk increases when individuals approach their maximum muscular capacities.

Effects of Pendulum Test Values (PTV) associated with different reference surfaces

The relationship between PTV and human slip responses were assessed. The investigation was associated with all RSs except for 2D17 which had a higher PTV value but inconsistent slip responses. In general, PTV and human slip responses were correlated (R^2=0.86). However, the four types of RSs present different configurations of friction features (and different friction mechanisms) to both the humans and the Pendulum tribometer; a PTV of 15 on a gritty but nominally flat porcelain enamel surface will not necessarily have a similar percentage of human slips as a 3D-profiled vacuum-formed plastic surface with a PTV of 15. Indeed, vacuum-formed RS 3D35 (PTV 15) had fewer slips than porcelain-enamel RS 2D13 (PTV 18).

CONCLUSION

Entering and exiting a bathtub/shower represent a significant slip/fall risk as measured by RCOF or Friction Demand and slip distance especially for older adults. Evidence suggests that older adults adopt more conservative strategies during obstacle crossing, however, this strategy as measured by stepping time indicates that the transition of the whole-body COM was delayed resulting in increased friction demand and slip distance (i.e., slip and fall risk). Age-related differences in whole-body and segmental control during obstacle crossing may place older adults at greater risk of imbalance during the transition from dry to wet floor surfaces.

FUTURE DIRECTIONS

Due to the complexities of interaction between humans and the different types of RSs (with their differing friction mechanisms), further human and tribometry studies of additional RS candidates is warranted.

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