

Portable Measurement Devices for Slip Risk Assessment: A Critical Gap Analysis and Design Requirements for a Next-Generation Device

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Abstract

Falls due to slipping are one of the costliest injuries in the workplace. The coefficient of friction (COF) between the worker's footwear and the floor is the main physical factor that determines slipping. There are two main categories of slip risk assessment (SRA) devices: laboratory-based devices that re-create the mechanics of walking, but which are not portable, and field tribometers that do not re-create human heel-strike kinematics. This paper investigates the reasons why no SRA device is simultaneously portable, biofidelic, and validated against human slip outcomes, and proposes design requirements for such a device. Literature was located through four databases (Scopus, Web of Science, PubMed, and IEEE Xplore). Through examining existing SRA devices according to three independent criteria: portability, biofidelity, and validation against human slips, it becomes evident that no current device fulfills all three criteria. The reasons for the lack of devices that fulfill these criteria are that wearable sensors rarely measure shear and normal force simultaneously between shoe-floor interactions, that environmental conditions are rarely incorporated into the measurements of those forces, and that portable SRA devices are almost never validated against

gait-laboratory reference data. Each of these factors presents quantified design requirements for the next generation of SRA devices, including a sampling-rate specification based on the measured frequency content of gait rather than from convention, and a validation protocol grounded in established statistics. This paper, therefore, presents a concrete design specification for such a device. This specification provides the criteria against which the next generation of SRA devices can be built and evaluated.

Keywords

Coefficient of friction; slip risk; tribometer; wearable sensing; gap analysis; design requirements

1. Introduction

Falls on the same level of ground are a major problem in terms of occupational safety. According to the 2025 Liberty Mutual Workplace Safety Index, falls on the same level are the second most costly form of disabling workplace injury in the United States, with annual cost estimates at around \$10.5 billion in 2025 (Liberty Mutual 2025). Most falls begin with a slip, and whether a slip occurs comes down to one physical relationship: the friction between the person's shoes and the floor relative to the friction that their gait demands at that given time (Redfern et al. 2001, Chang et al. 2016).

A slip occurs when the friction that the walker's gait demands (also known as the required coefficient of friction or RCOF), peaking just after heel contact, is stronger than the available coefficient of friction (ACOF) that the floor can provide. Studies measuring slips of 31 walkers on a near-marginal friction level have determined that for each 0.01 increase in required coefficient of friction, the odds of slipping increase about 1.7 times (Beschorner et al. 2016). The relationship is one of margin, not magnitude: on a marginal surface, any increase in the friction required by the gait of an individual relative to the friction provided by the ground will decrease the margin of safety that the individual has from slipping.

Furthermore, determining the COF with accuracy is a difficult task. SRA devices, in routine use, disagree with one another to a degree that would be unacceptable in most measurement contexts. In a comparison referenced against human walkers, only two of the nine tribometers correctly ranked the slipperiness of six different surfaces (Powers et al. 2007). Furthermore, another controlled study discovered that between 51 and 82% of the differences between the COF of a given surface and the COF that was read by the device was due to the operators of those devices, the devices themselves, or the specimens (often shoes) of the walkers, rather than the slipperiness of the surfaces tested (Siegmund et al. 2021). The devices that reliably predict human slips remain in the gait laboratory. Thus, while there are a variety of devices that measure COF, there are few field-deployable devices that can be trusted to accurately reflect the COF of a surface in the workplace.

Therefore, this paper will investigate the problem of slip prevention on the same level of ground and ask the question of which combination of sensing, environmental conditioning, and validation would let a device be portable, biofidelic, and validated against human slips, that is, match gait-laboratory accuracy in predicting them, all at the same time. Furthermore, what specifications must such a device have? The contributions of this article will be narrow to the field and focus upon providing a critical analysis of the current SRA devices for measuring COF, and into proposing a testable design specification and protocol for their validation: by treating portability, biofidelity, and validation as independent criteria and locating the region no current device reaches, the analysis turns a vague "measurement gap" into a discrete set of engineering design requirements against which a next-generation device can be designed and judged. Thus, by analyzing the current devices in relation to the problem, what is essentially a gap in the current devices and techniques, it will be possible to propose specific design requirements for the development of such a device. Section 2 presents the problem. Section 3 presents the scope and method to be utilized to investigate this problem. Section 4 presents the devices and their analysis in relation to this gap. Section 5 presents three barriers to solving this problem and the requirements for overcoming those barriers. Finally, Section 6 presents the conclusions of the article.

2. Framing the Measurement Gap

Two quantities must be kept distinct before any device can be judged. The ACOF is a property of the shoe-floor-contaminant interface, while the RCOF is a property of the walker. Predicting slips means relating the two, yet in most instances the device measures a proxy for ACOF under conditions chosen for repeatability rather than realism (Grönqvist et al. 2001). The literature that was published on these concepts some twenty years ago, however,

recognised the importance of this distinction: Chang, Grönqvist, and colleagues (2001) noted that static, low velocity drag methods for measuring COF were only applicable to dry, clean floors, and that contaminated floors required dynamic methods that reproduce realistic sliding speed, contact pressure, and the rate at which normal force builds at heel strike. There are three measurement principles that are commonly used, each of which differs precisely on these points, as is illustrated in Figure 1.

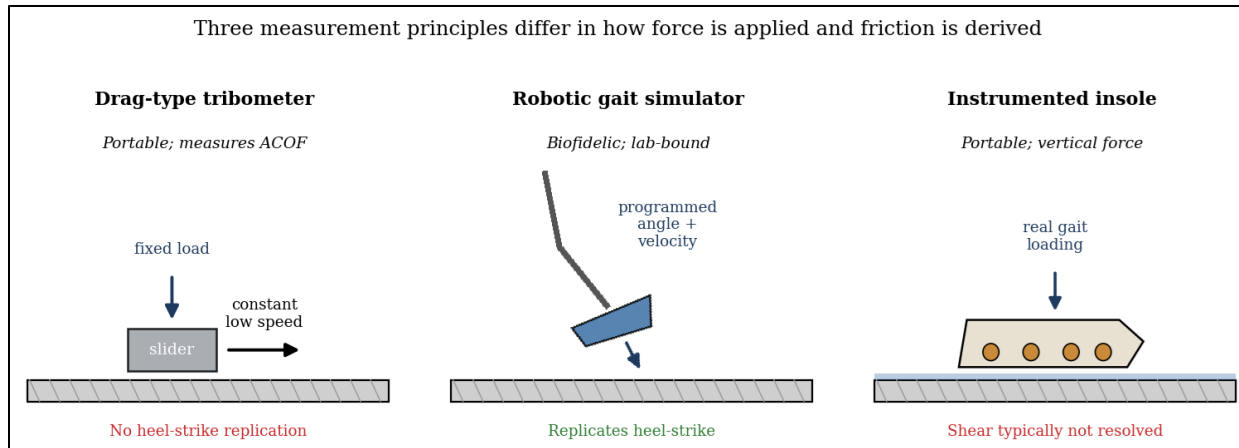


Figure 1. Three measurement principles: a portable drag-type tribometer (constant low speed), a lab-bound robotic simulator (reproduces heel-strike), and an instrumented insole (real gait, vertical force only).

The differences among each of the three concepts relate to the concept of lubrication of the shoes by the contaminated floor. For instance, Beschoner et al. (2009) modelled this as a mixed-lubrication contact. The model indicated that as the speed of the shoe over the contaminated floor increased, hydrodynamic lift grew, asperity contact shrank, and the COF decreased; the shoe rides partly on a pressurised fluid film rather than touching the surface directly. A tribometer sliding at an unrepresentative speed therefore reports a friction the walking foot never feels. A device can be highly repeatable yet systematically biased, which is exactly why the concept of agreement between devices must also be considered (Powers et al. 2007, Siegmund et al. 2021). Furthermore, these two concepts are independent of one another; a third concept must also be considered: biofidelity. Hence, three criteria should be considered for the development and implementation of SRA devices:

1. **Portability:** whether the device can be brought to the workplace and used on the actual floor in question; without it, measurement is confined to the laboratory and cannot inform site-specific risk;
2. **Biofidelity:** whether the device reproduces the heel-strike kinematics of human walking, such as contact angle, velocity, and loading rate; without it, the friction measured is not the friction the foot experiences;
3. **Validation:** whether the device's measurements of COF have been shown to appropriately and accurately predict slips of humans while walking on these different floors, not merely to agree with other instruments; without it, a reading has no demonstrated link to safety.

Each criterion is important, but an SRA device that is to be used in the field will need to meet each of these three criteria. As will be explained in the remainder of this paper, however, each of the currently existing devices for measuring anti-slip coefficients meets at most two of these three criteria. For these reasons, each of the three criteria will be considered as independent axes rather than folding them into one.

3. Scope and Method

This is a critical gap analysis. Databases searched included Scopus, Web of Science, PubMed, and IEEE Xplore, using combinations of coefficient of friction, slip resistance, tribometer, required coefficient of friction, wearable force sensing, and machine learning slip prediction. Purposive selection included sources that contributed to a foundational definition, a quantified device-performance result, or direct evidence bearing on one of the three gap axes. Standards documents were consulted in their current editions.

4. Device Families Against the Gap

Three device families exist: those used in the laboratory, those that are regulatory and compliance devices, and Field-deployable emerging systems, the third still largely aspirational. Laboratory reference standards consist of gait-laboratory force plates and robotic gait-simulating tribometers, which prioritise biofidelity and predictive validity. Regulatory and compliance devices include walkway tribometers and whole-footwear testers that prioritise standardisation and, for the walkway class, portability. Field-deployable emerging systems consist of instrumented insoles and portable sensor-fused prototypes, prioritising mobility but not yet demonstrating validated COF derivation. Table 1 maps representative devices onto these roles and the three gap axes.

Table 1. Device families mapped against the three gap axes. “Partial” denotes a capability present in principle but not validated for COF derivation during natural gait.

Device Family	Device Type	Biofidelity	Portability	Gait validation	Representative devices
Laboratory reference	Force plates	Very high	None	Gold standard	AMTI/Kistler force plates
	Robotic testers	High	Low	Demonstrated	NextSTEPS; DTU actuated setup
Regulatory	Whole-footwear testers	Low–moderate	Low	Bias documented	SATRA STM 603
	Walkway tribometers	Low	High	Weak / indirect	BOT-3000E; Mark IIIB; English XL
Field-deployable	Wearable/sensor-fused	Moderate (potential)	High	Absent	Instrumented insoles; sensor-fused prototypes

The most telling evidence for the gap is not that the device families differ in design but that the portable ones cannot be trusted to agree. Figure 2 summarises two findings that anchor this claim: a human-referenced comparison in which only two of nine tribometers passed (Powers et al. 2007), and a variance analysis attributing most of the measurement spread to the operator, unit, and specimen rather than the surface (Siegmund et al. 2021).

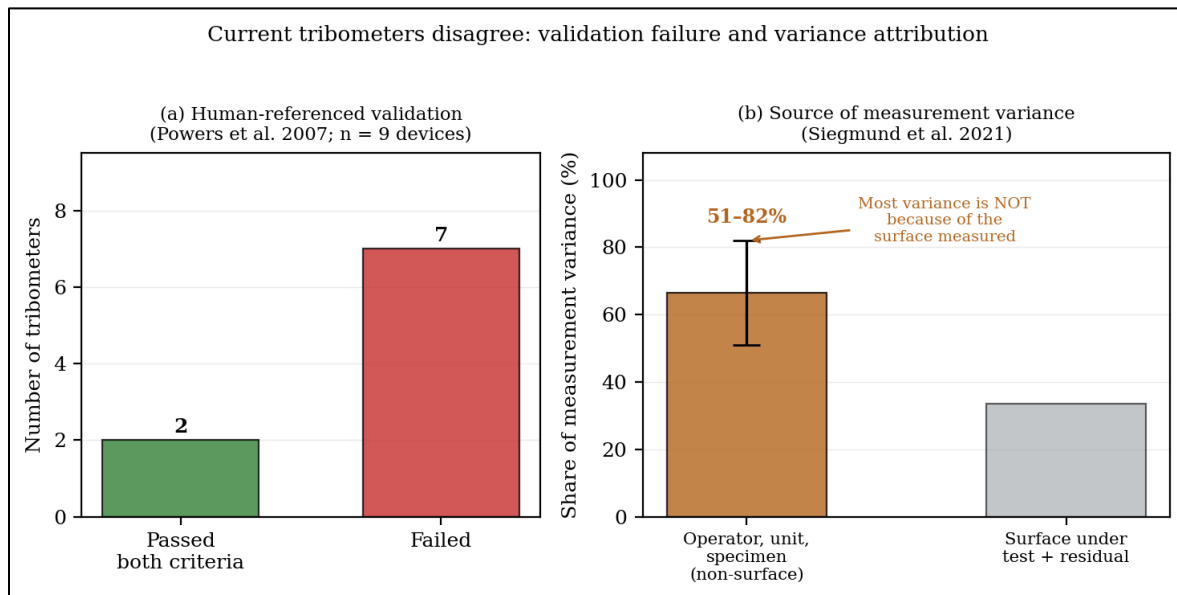


Figure 2. Current tribometers disagree. (a) Only two of nine devices met both validation criteria (Powers et al. 2007). (b) Operator, unit, and specimen account for 51–82% of measurement variance, not the surface tested (Siegmund et al. 2021).

4.1 Laboratory Reference Standards

The most common devices used in the laboratory are force plates, which measure the three-dimensional ground reaction force that results from walking on a flat surface and are the reference against which everything else is judged; their limitation is simply that they are fixed installations. Robotic gait-simulating tribometers close the realism gap mechanically. For instance, the NextSTEPS system can set the heel strike angle and velocity of a participant that walks on the device, and it more accurately predicts slips and achieves high sensitivity across participants with 66 different types of footwear on different types of floor and fluids, although at 18 kg it meets no occupational criterion for portability (Beschorner et al. 2023). Another tribometer is the DTU actuated force plate, which can simulate three different types of slips across six contaminant conditions, in accordance with the ISO 13287 standard (Jakobsen et al. 2022). Together, they show both the predictive value of biofidelity and its cost in mobility.

4.2 Regulatory and Compliance Devices

Tribometers used in regulatory environments include the BOT-3000E walkway tribometers, which are used to establish standards such as ANSI A326.3 (2022), and which are portable; however, the low constant-velocity slider used by these tribometers does not reproduce heel-strike mechanics, and different models of these tribometers return different results when testing the same type of footwear (Powers et al. 2007, Siegmund et al. 2021). Their real weakness is not that they ignore environmental variation but that, as routinely operated, they do not predict real-world slips reliably. Another type of regulatory device is the whole-footwear tester, such as the SATRA STM 603, which runs under ASTM F2913-24 and ISO 13287 and evaluates complete shoes under set conditions; Beschorner et al. (2019) showed that their predictive validity depends strongly on test angle and normal force, and Blanchette and Powers (2015) quantified their prediction bias directly.

4.3 Field-Deployable Emerging Systems

An emerging type of device is the instrumented insoles that travel with the wearer and capture real gait. The problem with insoles is that most can only measure vertical forces. The reason for this limitation is that the coefficient of friction is calculated from the shear and normal force between the shoe and the ground; without the ability to measure shear forces, insoles cannot calculate the coefficient of friction between the shoe and the ground, no matter how well they are validated for vertical load Cramer et al. (2022). The relevant wearables are the minority that attempt triaxial sensing, mainly piezoelectric shoe-sole arrays (Honda et al. 2019), soft 3D printed sensors that adhere to the shoe (Willemstein et al. 2025), and elastomeric or Hall-effect transducers that resolve shear as well as normal force. Portable sensor-fused prototypes combine such sensing with inertial kinematics and surface characterisation (Xiang et al. 2023). None of these devices have yet been validated against the ground reaction forces of the gait-laboratory RCOF measurements. This is the gap that is targeted in the present analysis.

5. Diagnosis and Design Requirements

The gap between current practice and true COF values is not an inherent constraint but the sum of three tractable engineering deficits design-wise. This section names each, attaches a quantitative anchor, and turns it into a design requirement. Each barrier below corresponds to one of the three criteria: the shear/normal sensing requirement restores biofidelity of the measured force, the sampling and conditioning requirements make that measurement representative rather than conventional, and the validation requirement supplies the missing link to human slip outcomes. Portability is the constraint threaded through all three so that every requirement must be met in a field-deployable form.

5.1 Barrier One: No Portable Simultaneous Shear-and-Normal Sensing.

Because COF is the shear force divided by normal force, both must be captured at the same place and instant. Force plates do this; few wearables do. Vertical-only insoles, however well validated for load (intraclass correlation above 0.94) in Cramer et al. (2022), cannot, by construction, yield COF. The few triaxial efforts show why it is hard: elastomeric and soft 3D-printed sensors resolve shear (Willemstein et al. 2025); Hall-effect transducers manage simultaneous normal and shear sensing but over modest pressure ranges. This results in a design requirement, R1: the device must measure shear and normal force simultaneously at the same sensing site, with shear-axis error characterised against a force-plate reference rather than inferred from vertical load.

5.2 Barrier Two: Sampling and Conditioning Chosen by Convention, Not Evidence

Specifications in this area often sample normal and shear force and kinematic data at high rates (often at 1000 Hz) without justification, yet the evidence does not support them for walking situations. The frequency content of gait is mostly low: Antonsson and Mann (1985) showed that gait signals concentrate at low frequencies; Giakas and

Baltzopoulos (1996) found about 95 per cent of vertical ground-reaction-force power below roughly 25 Hz; and Gruber et al. (2017) placed even the walking impact band below 20 Hz. Edwards et al. (2022) showed that 48 Hz is enough to recover the walking impulse. By the Nyquist criterion, a few hundred hertz is therefore ample for walking-based slip assessment, and specifying 1000 Hz spends power and storage without capturing anything real. This results in a design requirement R2: sample force and kinematics at a justified rate of about 200–500 Hz for walking, reserving higher rates for impact-transient or running analysis.

Environmental conditioning is the second half of this barrier. Contaminant film thickness, temperature, and humidity all shift measured friction (Beschoner et al. 2009, Chimich et al. 2021), and surface roughness correlates with COF strongly enough to act as a predictor: Kim et al. (2013) identified a functional roughness ceiling near 50 micrometres for soapsuds-wet floors, and ISO 25178-2 areal parameters give the modern vocabulary for quantifying it. This results in a design requirement R3: incorporate contaminant film thickness, temperature, humidity, and a surface-roughness descriptor as measured inputs rather than uncontrolled nuisance variables.

5.3 Barrier Three: Validation Against Devices Instead of Against People

The weakest part of current practice is that devices are validated against other devices, not against human slips. No published portable shoe-side COF device has been validated against concurrent gait-laboratory RCOF using formal agreement statistics. The method to do so is mature and borrowed from wearable biomechanics: the intraclass correlation coefficient, with the thresholds set by Koo and Li (2016), excellent agreement above 0.90, together with Bland and Altman (1986) limits of agreement. These must be applied to the right quantity: Cramer et al. (2022) validated vertical force, so their excellent Intraclass Correlation Coefficient (ICC) cannot be carried over to COF, which depends on shear. This results in a design requirement R4: validate the derived COF, not a surrogate, against gait-laboratory reference across at least 20 participants and three types of footwear surfaces, reporting ICC and Bland-Altman limits for COF itself, targeting excellent agreement (intraclass correlation coefficient above 0.90) and limits within ± 0.05 COF units.

5.4 Future Direction: Machine Learning as an Enabler

Machine learning (ML) increasingly links sensor data to slip prediction, but its current performance is modest and should be reported plainly. On glycerol-contaminated surfaces, a support-vector classifier reached only 0.68 accuracy on a 37-outsole pilot set, image-based convolutional models for winter footwear reached 0.93 on 89 samples, and intelligent-insole systems classify slip risk across dry, wet, soapy, and oily conditions using sensor fusion (Yamaguchi et al. 2022, Xiang et al. 2023). Reported error must be propagated to COF rather than quoted against peak force, since a 15 per cent force error can translate into a COF error above 0.06, larger than the 0.01 increments, that materially shift slip odds. This results in a design requirement, R5: treat machine-learning outputs as calibrated COF estimates with propagated uncertainty, trained and tested across the contaminant conditions of intended use, with stated sample sizes.

Taken together, the five design requirements describe a device rather than a wish list. The requirements are summarized as:

- **Simultaneous shear and normal sensing (R1):** measure both force components at the same site at once; characterise shear error against a force plate, not infer it from vertical load.
- **Evidence-based sampling (R2):** sample force and kinematics at ~ 200 –500 Hz for walking; reserve higher rates for impact or running.
- **Environmental inputs (R3):** treat temperature, humidity, and surface roughness as measured inputs, not nuisance variables.
- **Gait-lab validation (R4):** validate the derived COF (not a surrogate) against a force-plate reference; ≥ 20 participants, 3 surfaces; report ICC and Bland–Altman, targeting ICC ≥ 0.90 and limits within ± 0.05 COF.
- **Calibrated ML outputs (R5):** report ML results as calibrated COF estimates with propagated uncertainty, trained/tested across intended contaminant conditions, with sample sizes stated.

Figure 3 shows how they map onto a functional architecture: a wearable sensing layer (R1, R3), synchronous acquisition at an evidence-based rate (R2), validation against gait-laboratory reference (R4), and data-driven friction estimation (R5).

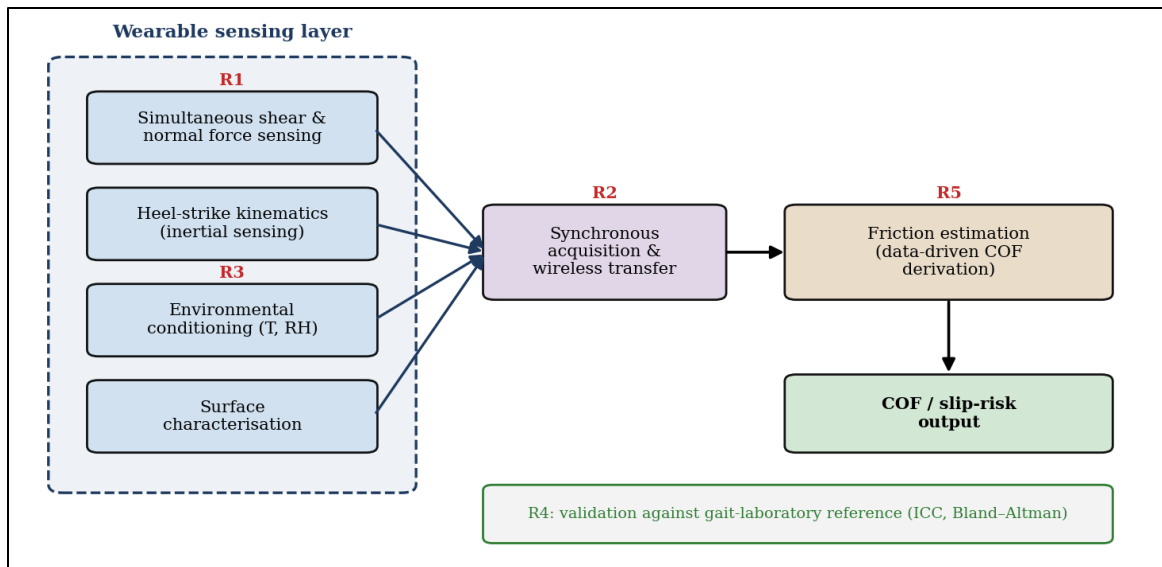


Figure 3. Functional architecture of a portable biofidelic SRA device, showing where requirements R1 to R5 apply.

6. Conclusion

The current available SRA devices for measuring shoe-floor friction sit at the extremes, realistic but immobile, or portable but unrealistic, and leave the most useful combination unreached. This paper has argued that the gap is not fundamental but the sum of three specific, measurable deficits: no portable simultaneous shear-and-normal sensing; conditioning and sampling chosen by convention rather than by the frequency content of gait; and validation against other devices rather than against human slips. Each has been turned into a quantified requirement (R1–R5) that a candidate device must meet, together with a protocol for judging it. These requirements are literature-derived and remain to be confirmed empirically. Their value extends beyond any single prototype: adopted as a shared specification, they would make future portable-SRA devices comparable to one another and to gait-laboratory reference, directly addressing the inter-device disagreement that undermines current field measurement.

The enabling technologies are individually mature: triaxial micro-force sensing, low-power wireless acquisition, and machine-learning estimation each already perform useably on their own. No group has yet combined all three into one validated, portable, biofidelic device; mature parts are not an integrated whole and achieving that integration is the open problem this analysis defines. Stating the requirements precisely has a practical payoff, a device built to them can be judged against criteria fixed in advance rather than chosen to flatter the result. Given that falls on the same level cost an estimated 10.5 billion US dollars annually, a portable SRA device that measures friction as the foot experiences it would translate directly into better-targeted slip prevention. Building and validating such a device against gait-laboratory reference is the future direction of slips, trips and falls prevention.

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