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Evaluation of an actuated force plate-based robotic test setup to assess the slip resistance of footwear

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ABSTRACT

Slipping is a frequent cause of occupational accidents. This is often due to an insufficient available coefficient of friction (ACOF) of footwear. The aim of this study was to present a footwear ACOF test setup, and to evaluate it based on device requirements presented in the ISO 13287 test standard. One left Airtox TX2 shoe underwent slip resistance measurements under three test modes (Forward flat slip, backward slip on the forefoot at angled contact and forward heel slip at angled contact), with six contaminant conditions (dry steel, dry tile, glycerine on steel, glycerine on tile, canola oil on steel and canola oil on tile). The test setup was successfully able to measure ACOF in close accordance to the ISO 13287 test standard with a good repeatability. Furthermore, the test setup can alter biomechanical and tribophysical testing conditions, which may provide more valid footwear ACOF measurements in the future.

Relevance to industry: The setup can accommodate biomechanical and tribophysical testing conditions, hence the setup can be a tool for accessing more valid ACOF measurements - closer to real world slip events. Footwear manufactures or researchers, with the goal of improving footwear slip resistance, can implement the setup.

1. Introduction

Fall accidents on the same level account for 22.4% of all serious work related accidents, reported in the period 2012–2016 in Denmark (Arbejdstilsynet, 2017). Annually, injuries attributed to falling accounts for expenditures of approximately 3.9 billion DKK in lost production costs (Sundhedsstyrelsen, 2016). The same challenge is present in other western countries, including the UK, USA and Sweden, where especially the aging part of the work force is at risk (Chang et al., 2016; Courtney et al., 2001). When many work related injuries are decreasing, the amount of fall accidents are increasing (Chang et al., 2016; Zhao et al., 2021). In fact, the Liberty Mutual Workplace Safety Index showed that the direct cost of disabling workplace injuries, related to falls on the same level was US$9.19 billion in 2012 (Liberty Mutual Workplace Safety Index, 2012, 2019). In 2021 the cost has increased to US$10.58 billion (Liberty Mutual Workplace Safety Index 2012, 2019). Slipping is acknowledged as the most significant cause of fall accidents (Courtney et al., 2001) and therefore prevention of slipping has a great potential to reduce the occurrence of occupational accidents (Beschorner and Singh, 2012).

The occurrence of a slip becomes less likely to occur when the available coefficient of friction (ACOF) exceeds the required coefficient of friction (RCOF) (Hanson et al., 1999). Here, the RCOF can be determined by dividing the horizontal force with the vertical force, during walking across a force plate under slippery conditions (Beschorner et al., 2016; Cham and Redfern, 2002; Yamaguchi and Masani, 2015). In contrast, the ACOF is commonly determined by mechanical testing during which a footwear sample is dragged across a floor surface (Iraqi et al., 2018a, 2020).

Measurement results for ACOF differ substantially dependent on the test setup and test conditions (Chang et al., 2001). To accommodate these variations, the "ISO 13287:2019 - Personal protective equipment – Footwear – Test method for slip resistance" was established (ISO 13287, 2019). Commercially available test devices, such as the STM 603 (Satra Technology, Kettering, Great Britain) and the DW9530 (Fanyuan Instrument, Hefei, China) can operate in accordance with the ISO

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13287:2019 test standard. Both devices are designed with a force transducer positioned above a shoe last. In biomechanics, however, a force plate is considered the golden standard to evaluate the acting forces between footwear and floor (McLaughlin, 2013). To the authors' knowledge, only the STEPS ('Shoe Tribometer for Enhancing Predictive Safety', XRDS Systems, LLC), uses a force plate (Jones et al., 2018). A test device incorporating this established method for the assessment of ACOF in footwear is therefore expected to provide the highest "transmissibility" to RCOF, where this same equipment is already used.

Overall, this leads to the aim of this study, which was to design a force plate-based ACOF test setup, and evaluate it based on device and setup requirements presented in the ISO 13287 test standard.

2. Method

With the aim of designing a force plate-based ACOF test setup, we instrumented a force plate atop of a robotic hydraulic platform (van Doornik and Sinkjaer, 2007). Testing parameters and device requirements was performed in accordance to the ISO 13287 standard (Table 1) (ISO 13287, 2019).

2.1. Device description

The experimental setup consisted of a steel frame (Fig. 1 E) designed to maintain a fixed position of a shoe (Fig. 1 A) above a force plate (Fig. 1 B) (AMTI- OPT464508HF-1000, Advanced Mechanical Technology, Inc. Watertown MA, USA). The manufacturer states a measurement accuracy of ±0.1% of the applied load (up to 4448 N) (Advanced Mechanical Technology Inc). The force plate was mounted atop of a hydraulic platform (Serman-Tipsmark, Brønderslev, Denmark), able to move along the vertical and horizontal axes (Fig. 1 Z and Y) at velocities ranging from 0 to 1 m/s (van Doornik and Sinkjaer, 2007). The hydraulic platform was movement and velocity controlled in Mr. Kick (v. 3.0, Aalborg, Denmark). Additionally, a retroreflective marker was placed on the hydraulic platform to capture platform movements using an eight-camera motion capture system (Qualisys Oqus 3+ and QTM, 2019 software, Qualisys Gothenburg, Sweden). Force plate and movement data were recorded with a 1000 Hz and 500 Hz sample rate, respectively.

A plastic shoe-last size 43 EU (Framas, Pirmasens, Germany) was fixed directly under a linear guide (Fig. 1 G), with a rod attached to the frame with linear bearings. This enabled movement in the vertical direction. Normal load was applied to the linear guide through a vertical force distributer using standard weight plates (Fig. 1 F). Non-restricted vertical movement of the lead was ensured by applying PTFE foil on the surfaces of the linear guide and the inner support frame, which maintain the horizontal position of the shoe. Additionally, a PTFE based oil (Kema Oil, PTFE TRI-17) was applied to the PTFE surfaces to allow for smooth and low friction contact.

Table 1
Test setup requirements.

	Requirements according to ISO 13287
1	Normal force 400–500 ± 25 N
2	Accuracy of device for friction measurement of 2% or better
3	Sliding velocity of 0.30 ± 0.03 m/s
4	Static contact time between initial contact and start of movement of ≤1.0 s.
5	Measurement period shall start within 0.3 s of achieving the full normal force and end 0.6 s after start of movement.
6	Shoe contact angle at 0 and 7.0 ± 0.5°
7	Measurement period shall start within 0.3 s of achieving the full normal force.
8	Able to include wet contaminants
9	Able to apply tile (Eurotile 2) and steel surface (Rz between 1.6 μm and 2.5 μm)

2.2. Preparation and cleaning

The procedure of the test and preparation of footwear and floor was in accordance to the specification of ISO 13287. Hence, the shoe was sanded with 400 grit paper, cleaned using an ethanol solution, scrubbed with a clean medium stiff brush, washed with demineralized water and dried using clean dry compressed air and then at ambient temperature (23 ± 2 °C). Surfaces were cleaned with an ethanol solution, scrubbed gently with a clean medium stiff brush, rinsed with demineralized water and dried using clean dry compressed air and then at ambient temperature.

2.3. Surfaces

Two surfaces were used in the setup. One ceramic tile (Eurotile 2 specified in ISO 13287) and a steel plate number 1.4301 with a mean roughness (Rz) of 1.65 μm. The steel plate roughness is measured using a surtronic 25 profilometer (Taylor Hobson, Leicester, United Kingdom) in accordance with the specifications from ISO 13287, which implies 10 measurements at different locations in the direction of sliding movement. The mean roughness (Rz) must be between 1.6 μm and 2.5 μm according to ISO 13287. The 10 measurements were measured in accordance with ISO 4287 (ISO, 1997).

2.4. Footwear

The left shoe from a pair of size EU 43 Airtox TX2 (Airtox, Virum, Denmark) safety footwear was used for evaluation of the test setup.

2.5. Testing conditions

The shoe was exposed to three different test modes (Fig. 2) (Forward flat slip, backward slip on the forefoot at angled contact and forward heel slip at angled contact), with six contaminant and surface combinations (dry steel, dry tile, glycerine on steel, glycerine on tile, canola oil on steel and canola oil on tile). A 7° aluminium wedge was constructed in accordance with the specifications of ISO 13287, to control shoe/surface contact angle before testing.

In total, this sums up to 18 different conditions. Five slip resistance measurements were taken for all test conditions, leading to 90 measurements in total. Five measurement repetitions for each condition in accordance with the ISO 13287.

2.6. Test procedure

The platform was resting in the starting position between 0.0 s and 0.5 s and no external forces acted on the force plate (Fig. 3, event 1). At 0.5 s the platform moved upwards in the vertical direction and initial contact between shoe and surface was reached (Fig. 3 event 2). At 0.8 s the shoe was resting statically on the surface (i.e., full normal load reached) (Fig. 3 event 4). After 1.0 s the platform started moving in the horizontal direction (from forfoot to heel) with a constant velocity of 0.298 ± 0.01 m/s (Fig. 3 event 5). The friction measurement period started at 1.1 s and ended at 1.3 s (Fig. 3 event 5–6). The horizontal movement ended at 1.35 s and corresponded to a moving distance of 120 mm (Fig. 3 event 7). From 1.35 s to 2.2 s the platform was static (Fig. 3 event 8). In the time interval 2.2–2.5 s the robotic platform moved horizontally (heel to forefoot) in the horizontal direction to prevent overshooting of the hydraulic rams (Fig. 3 event 9). After 2.5 s the platform moved back towards the starting point.

All dry (non-contaminated) measurements were performed first. Surface and shoe were wiped with isopropyl alcohol after every five measurements under dry conditions. During contaminated conditions, the surfaces were wiped clean for every five measurements and fresh contaminants were reapplied. Shoe and surfaces were thoroughly cleaned with soap and rinsing water when changing between glycerin

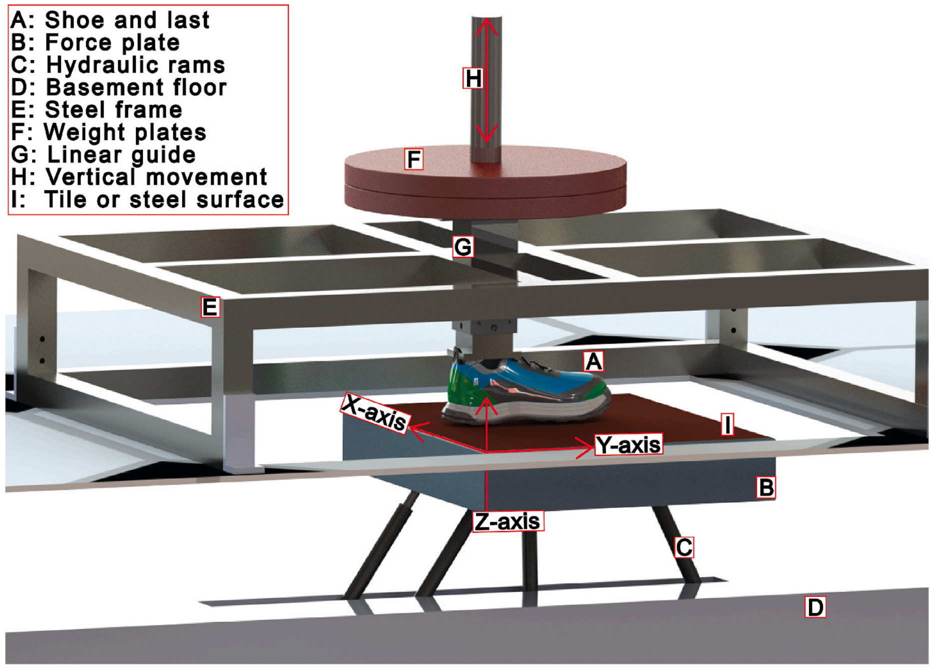

Fig. 1. Illustration of test setup.

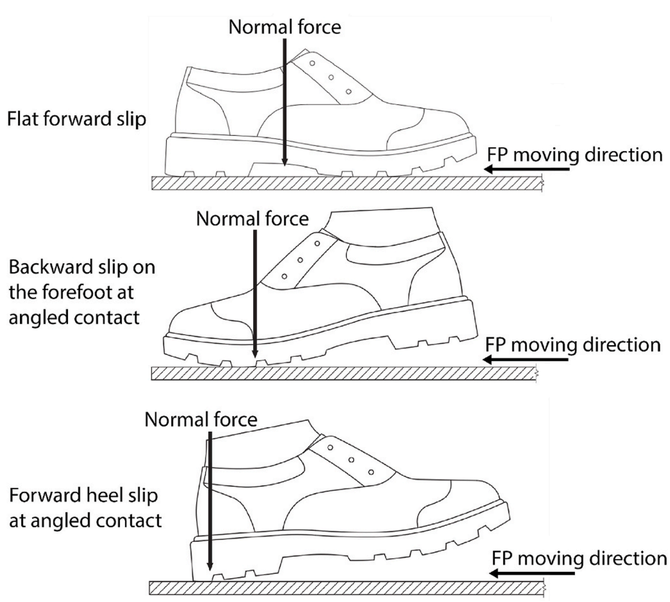

Fig. 2. Footwear orientation and force plate (FP) sliding direction. Adapted from ISO 13287 with permission from Danish Standards (ISO 13287, 2019).

and canola oil contaminants.

2.7. Data processing

Force and movement data were imported into MATLAB version R2020b (MathWorks, Massachusetts, USA) and processed in a customized script. Force and movement data were filtered with a second order low pass filter with a cut-off frequency of 20 Hz and 10 Hz, respectively. Force and movement data were synchronized by calculating the cross covariance and aligning data via circular shift. Beforehand 10 platform cycles were performed without shoe contact for both the steel and tile surface mounted atop.

These 10 platform movements without shoe contact were averaged and subtracted from the friction measurements. This was done to account for the inertia generated when the force plate was accelerated (Oliveira et al., 2017). The dynamic coefficient of friction (DCOF) was calculated by dividing the horizontal reaction forces, F_x and F_y (friction forces) with the vertical reaction force F_z (normal force) (Equation (1)).

$$DCOF = \sqrt{\frac{F_x^2 + F_y^2}{F_z^2}} \tag{1}$$

The mean DCOF for five measurements was calculated as function of time. Lastly, the corresponding mean DCOF in the measurement period (Fig. 3 event 5–6) was calculated and presented as an average and standard deviation.

3. Results

An entire movement cycle of the robotic platform generated three force components (Fig. 4). Bold solid lines are the mean reaction forces (blue = vertical force Z-axis; green = horizontal force Y-axis; red = horizontal force X-axis) and thin solid lines are the corresponding standard deviations. No contact forces were present between 0.0 s and 0.5 s (Fig. 4 event 1). Both the horizontal force components (Fig. 4 green and red) and the vertical force component (Fig. 4 blue) fluctuates at 0.5 s, when the robitic plateform started moving. At 0.6 s a peak appeares in all three force components due to the rapid contact between shoe and surface. The force components stabilizes at 0.8 s at ~500 N (Fig. 4 event 3).

When the horizontal movement started at 1.0 s (Fig. 4 event 4) the horizontal Y and X force components rises, with the Y component being the dominant. Simultaneously, the vertical Z force component fluctuates shortly. All three force components reached a plateau between 1.2 s and 1.3 s. After 1.35 s (Fig. 4 event 7) all force components are fluctuating slightly as the platform movement ends.

From 1.35 s to 2.2 s (Fig. 4 event 8) the robotic platform was static and the vertical Z force component and the horizontal X force component were static. The horizontal Y force component moves towards 0 as the compression between shoe and surface decreases. After 2.2 s the robotic platform moved horizontally (heel to forefoot) and the horizontal Y force component changes direction (Fig. 4 event 9).

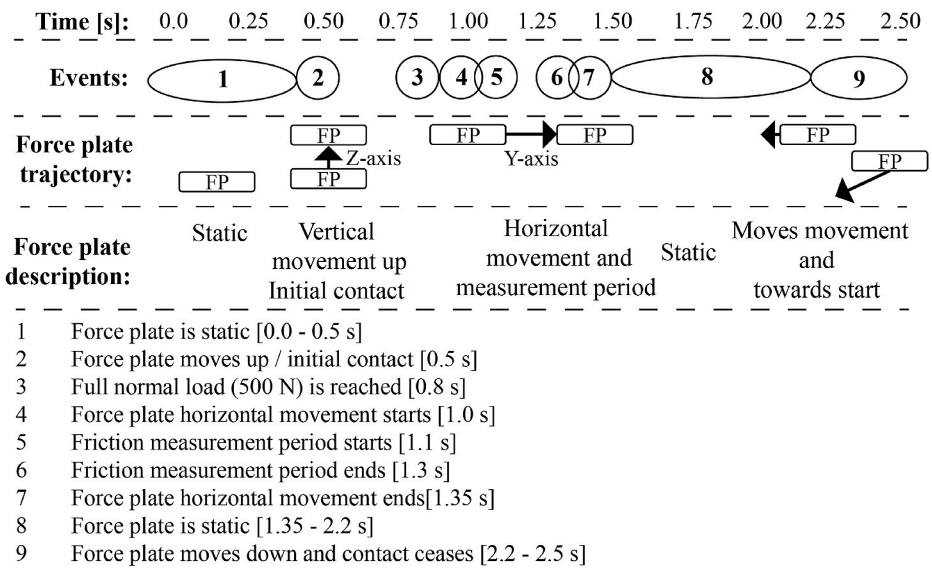

Fig. 3. Illustration and description of platform movement cycle.

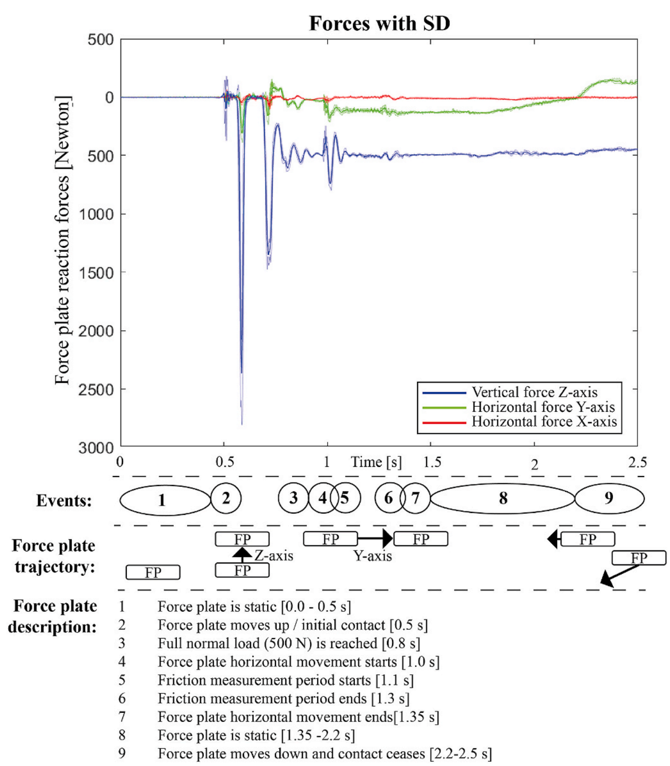

Fig. 4. Vertical and Horizontal force components for an entire robotic platform movement cycle. Bold solid lines are the mean reaction forces (blue = vertical force Z-axis; green = horizontal force Y-axis; red = horizontal force X-axis). The thinner solid lines represent the corresponding standard deviation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

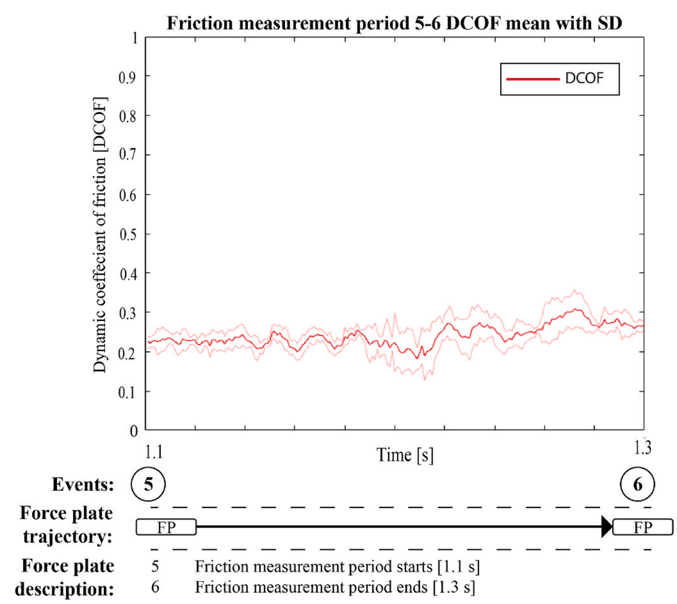

Fig. 5. Calculated DCOF as function of time with illustration of force plate trajectory for time interval 5–6 in the measurement cycle. Bold red solid lines are the mean dynamic coefficients of friction and thin red solid lines are standard deviations. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The calculated DCOF is represented by the solid red line from (Fig. 5 event 5–6). The DCOF fluctuates between ~0.2 and ~0.3 in the friction measurement period.

In general, the conditions without contaminants had higher DCOF compared to the conditions without. The highest DCOF was 0.93 and was found in forward heel slip at angled contact on the steel surface without contaminants. The lowest DCOF was 0.13 found in the backward slip of the forefoot on the steel surface - with glycerin as contaminant (Fig. 6; Table A1). Highest standard deviation (0.03) is found in forward heel slip at angled contact on the steel surface without contaminants. Lowest standard deviation (0.01) is found in backward slip on the forefoot on the Eurotile surface with glycerine as contaminant. Absolute values of mean dynamic coefficient of friction and standard deviation for all tested conditions are shown in appendix (Table A1).

4. Discussion

This study presents a new test setup for determining footwear ACOF measurements in close relation to the ISO 13287. The test setup repeatability is considered good with standard deviations below 0.03

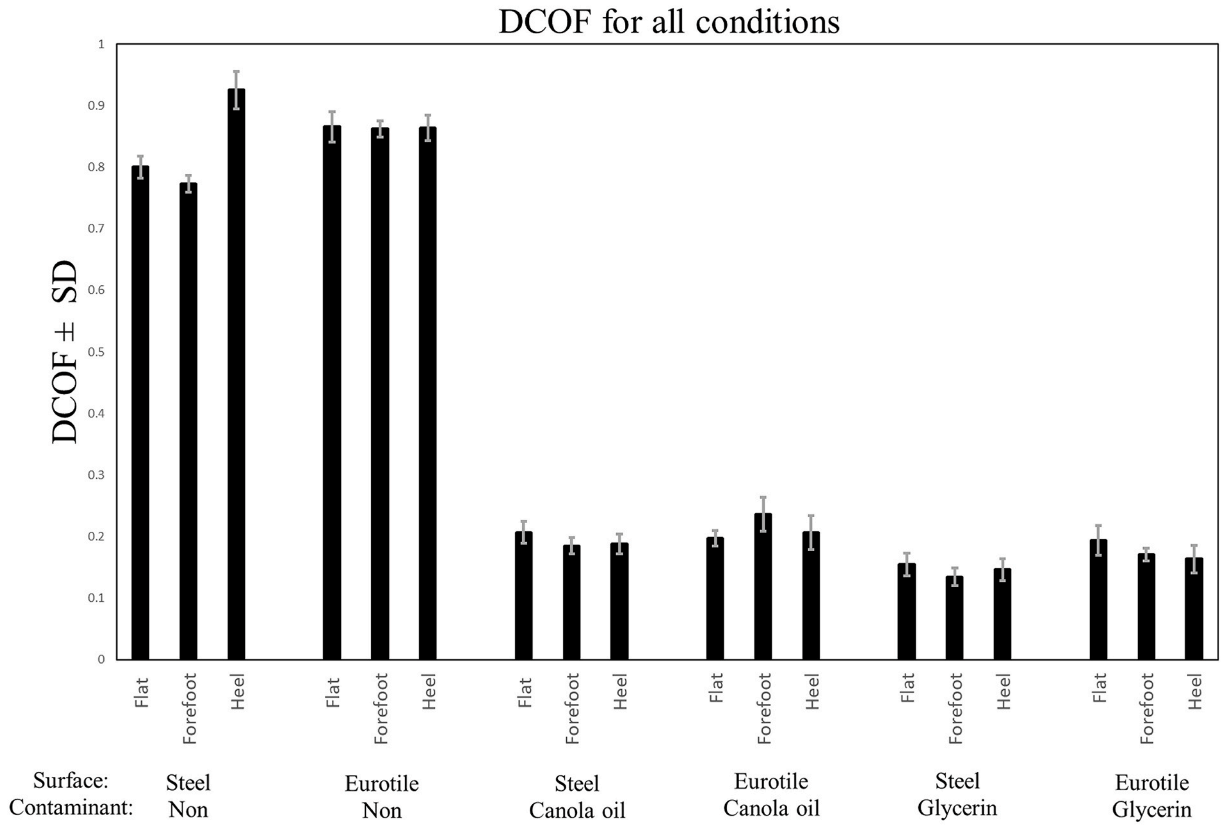

Fig. 6. Mean dynamic coefficient of friction for all tested conditions ± standard deviation.

(min: 0.01 max: 0.03) for all conditions. The test setup repeatability is similar to other slip resistance test devices presented in the scientific community (Aschan et al., 2005).

Even though the presented test setup is assessed capable of performing in close relation to the ISO 13287, the testing parameters from the standard, may not be the most valid for predicting the ACOF (Chang et al., 2001) This is supported by research, which suggests contact pressure between 200 and 1000 kPa (Chang et al., 2001). Sliding velocity is recommended between 0 and 1 m/s (Chang et al., 2001) or 0.5–1 m/s (Hunwin et al., 2010). Static contact time is recommended at maximum 600 ms (Chang et al., 2001) or 0–250 ms (Grönqvist et al., 2003). Lastly, shoe/surface angle is recommended at 17° (Iraqi et al., 2018a), 13° (Beschorner et al., 2019) and 14.7° (Albert et al., 2017). Thus, a wide range of relevant testing parameters have been used in the scientific literature, which may be more suitable for predicting the ACOF of footwear.

An obvious advantage of test setup consisting of a movable force plate is the apparent high degree of flexibility. This could potentially allow us to alter biomechanical and tribophysical conditions such as; normal load, sliding velocity, shoe/surface angle, static contact time and different surface/contaminant conditions, which all independently have been shown to change footwear friction behavior (Chang et al., 2001).

The test setup represented in this study should be able to accommodate these alterations, with the velocity- and acceleration-controlled robotic platform (van Doornik and Sinkjaer, 2007). The force platform can tolerate normal load ranges from 250 N to 4448 N, sliding velocity between 0 and 1 m/s and heel contact angle between 0 and 45° and static contact time between 0 and 1 s. It should be noted that with an increasing sliding velocity, a decrease in friction measurement period (Fig. 3 event 5–6) would be inevitable, due to the total robotic platform displacement distance of 120 mm in this setup. Modifications to the steel frame has to be made to accommodate the maximal robotic platform displacement distance of 200 mm. However, as long as the vertical and horizontal forces reaches a plateau, the DCOF calculation should be considered acceptable.

Due to the maximal displacement distance of 120 mm, requirement 5 (Measurement period should be between 0.3 s after start of movement and end 0.6 s after start of movement), could not be met. The 120 mm horizontal displacement caused an elapsed movement time of 0.35 s. Thus, a delay of 0.3 s from movement start to the beginning of the measurement period was not possible in this particular setup. This also led to a measurement period of 0.2 s instead of the 0.3 s suggested in the ISO 13287. Nonetheless, this time interval can be argued to be relevant, since slipping events have been shown to start between 30 and 50 ms after initial heel contact (Iraqi et al., 2018b). Averaging measurement period in the range of 0 ms (representing the instant that all targeted testing conditions were reached) to 200 ms is argued to be reasonable (Beschorner et al., 2020). Additionally, the force measurements did reached a plateau in the friction measurement period (event 5–6) making the friction measurement considerably sufficient.

In the present setup, the floor (platform) is moved upwards towards the shoe, and thus opposite other slip resistance tribometers where the shoe is pressed downwards against a force plate (Jones et al., 2018). The shoe was therefore allowed free vertical movement to avoid overloading (and failure) of the entire system. This means the only apparent damping in the system is caused by the deformation of the shoe. This system could be further optimized by implementing a damper in the system (e.g. a compression spring) in the linear guide. This would likely reduce the observed sinusoidal force fluctuation after initial contact [0.8–1.3 s]. Most of the observed force fluctuation is, however, diminished before the DCOF measurement period [1.1–1.3 s], and not considered a major limitation to the measurements.

Despite the high flexibility to e.g.vary the testing conditions, the present test setup in its total is an expensive construction with several practical limitations: Firstly, maintaining the hydraulic machinery is relatively expensive with an annual maintenance cost of approximately

2300 USD. Secondly, the hydraulic actuated platform is permanently installed in the floor (van Doornik & Sinkjær). This requires external oil supply, which implies tubes for oil supply are installed into the floor and attached to an external oil pump located in a separate room. This oil pump also generates considerable heat and noise and should be located away from adjoining office rooms etc.

5. Conclusion

This study presented a new robotic force plate-based footwear slip resistance test setup. The design was largely able to accommodate the footwear friction device requirements stated in the ISO 13287, Personal protective equipment - Footwear - Test method for slip resistance. The test setup showed good repeatability with low standard deviations for all testing conditions. DCOF results were comparable to previous findings and this setup is therefore considered applicable for footwear slip resistance determination. Moreover, the design of this system allowed for a large degree of flexibility to vary the testing conditions. This is relevant then testing footwear slip resistance under biomechanically and tribophysical relevant conditions.

Author contributions

Lasse Jakobsen: Investigation, conceptualization, software, visualization, original draft, writing - review & editing, funding acquisition.

Filip Gertz Lysdal: Investigation, software, original draft, writing - review & editing.

Timo Bagehorn: Investigation, original draft, software.

Uwe G. Kersting: Conceptualization, supervision, writing - review & editing.

Ion Marius Sivebaek: Funding acquisition, supervision, writing - review & editing, project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A.1
Mean DCOF ± SD for all conditions.

Contaminant/Surface	Test modes	DCOF (±SD)
None/Steel	Flat	0.80 (0.01)
	Forefoot	0.77 (0.01)
	Heel	0.92 (0.03)
None/Eurotile	Flat	0.87 (0.02)
	Forefoot	0.86 (0.01)
	Heel	0.86 (0.02)
Canola oil/Steel	Flat	0.21 (0.02)
	Forefoot	0.18 (0.01)
	Heel	0.19 (0.02)
Canola oil/Eurotile	Flat	0.20 (0.01)
	Forefoot	0.24 (0.03)
	Heel	0.20 (0.03)
Glycerin/Steel	Flat	0.15 (0.02)
	Forefoot	0.13 (0.01)
	Heel	0.15 (0.02)
Glycerin/Eurotile	Flat	0.19 (0.02)
	Forefoot	0.17 (0.01)
	Heel	0.16 (0.02)

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