Biomechanical Gait Analysis for the Extraction of Slip Resistance Test Parameters

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Received November 27, 2008 and accepted April 21, 2009

Abstract: Falling accidents caused by slipping represent a high proportion of all accidents and are cost intensive in industry as well as in the private sphere. To prevent such accidents, the slip resistance of flooring must be evaluated. Therefore, measurement methods are necessary. These methods must provide results that comply with an individual's perception of when a floor is slippery. This article describes the analysis of human walking motion to derive essential parameters and estimate their values for measuring the slip resistance of flooring. Human walking motion of 22 persons is analysed to discover the critical phases for slipping. The heel strike was extracted as the critical phase for falling accidents caused by slipping. A model of the friction between the shoe and flooring is set up to describe the conditions in that phase. Heel strike velocity, requirements quotient and contact pressure are extracted as essential parameters from the friction model. With the biomechanical gait analyses of the walking of more than 170 single steps made by 22 test persons, values for these parameters are derived. Suggestions are made to adopt these values as test parameters for slip resistance test devices.

Key words: Slip risk, Floors, Slip resistance, Test procedure, Test equipment, Walking analysis, Gait

Introduction

Over the years, falling accidents have led the statistics as the number one of all accidents. In Germany 20% of all accidents in industry are falling accidents caused by slipping, stumbling or tripping¹⁾. In the private sphere, 27% of all accidents are falling accidents. This accounts for a high percentage of accidents too²⁾. More than half of them (52%) are caused by slipping³⁾. 53% of all accidents occur inside buildings³⁾.

Falling accidents caused by slipping are not of minor severity as often shown in slapstick films. The consequences are usually more severe than expected. The average absence time from the workplace caused by falling accidents is about 20 d, and a quarter of these accidents leads to pension payments from the employers' liability insurance association¹⁾.

Studies⁴⁾ show that most of the accidents do not occur on contaminated floorings (oil, etc.) as often supposed.

Most of the slipping accidents occur on dry flooring (48%), followed by ice and snow (18%), wet flooring (17%) and "other", such as cleaning agents (9%) and oil (8%). Therefore, the measuring of slip resistance appears to be necessary on both dry and wet flooring surfaces.

Often it is difficult to perceive the slipperiness of floorings because it is not made evident by a glossy surface. Therefore, the slip resistance of floorings needs to be evaluated by precise measurements. This article will extract essential parameters and their values for the measurement of slip resistance by studying human walking with biomechanical analysis.

Walking of persons was analysed, for instance, by Hanson⁵⁾. To develop parameters for a procedure of measurement of slip resistance it was necessary to analyse a large set of biodynamical parameters of walking in a sufficient number of test persons under well known walking conditions. Therefore, a biodynamical test was carried out with more than 170 single steps of 22 persons. In the test the critical phase of walking (the heel strike) was recorded with a high speed camera. The heel strike velocities and angles of the test persons, as well as the

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contact area of the shoe sole, were analysed. The forces applied to the floor by the test persons were measured with a force-plate.

Subjects and Methods

Walking process

Human walking is one of the most unsafe modes of natural motion. Especially critical are the points when one foot breaks contact or comes into contact with the flooring surface. Heel strike is the more dangerous moment because slipping cannot be corrected by a balance movement of the body. At the beginning of the pendulum movement (lift-off of the foot) the center of gravity is in front of this foot and moves in the direction toward the supported foot^{6, 7)}. Therefore, slipping forward in the lift-off phase can mostly be corrected by moving the body.

Friction model for walking process

It is too complex to model human walking perfectly in a mobile test device⁸⁾. Consequently, it is necessary to reduce all of the influencing factors of slipping to those that are essential by modelling and to realise them in a test device. A possible model for describing the hazard of slipping is the friction model between shoes and flooring.

The essential parameters for the tribological model can be found in Fig. 1. To move the body the person must transfer the vertical force F_Y and the horizontal forces F_X , F_Z from the shoe to the floor. The quotient between vertical and horizontal forces is defined as requirements quo-

tient Q .

The most important value for the decision of whether slipping will occur is the friction force as a quality of the contact of the shoe with the flooring. To prevent slipping the friction force must have a higher value than the horizontal forces F_X , F_Z . The higher the difference between the dynamic coefficient of friction and the requirements quotient, the more safe the walking is. Slip-blocking is sufficient if,

$$\mu > Q.$$

To test the slip resistance of flooring, the dynamic coefficient of friction will be measured in the test device and compared with the requirements quotient in the form of the limits of the dynamic coefficient of friction. The horizontal heel strike velocity equals the parameter sliding velocity in the test device. The contact area of the heel is represented by the area of the sliders, and the shoe sole is the slider material for the device. Table 1 shows

Table 1. Parameters of movement versus parameters for the testing device

Parameter of movement	Test parameter
Requirements quotient	Dynamic coefficient of friction
Heel strike velocity	Sliding velocity
Contact area of the heel	Area of the sliders
Surface pressure (normal force/contact area of the heel)	Surface pressure (weight force/slider area)
Sole material	Slider material

Fig. 1. Parameters of movement versus parameters for the testing device.

the essential parameters of human walking versus the parameters for the testing device (Fig. 1).

Biomechanical studies

The aim of these studies was to find values for the parameters that are essential to calculate the risk of slipping and to determine parameter values for measuring the slip resistance of floors. Consequently, the moment of the heel strike of the foot is of special interest.

The following parameters were of interest:

- Walking velocity
- Horizontal and vertical forces applied to the floor
- Heel strike velocity
- Heel strike angle
- Contact area of the heel and fore sole.

On a gangway, the time-dependent forces, velocities and angles, as well as the walking velocity of the test person, were measured.

Measurement of the forces

The test gangway had a length of 5 m. Located 3 m from the beginning of the walkway, there was a multi-component piezoelectrical force plate (3-koordinates, Fa. Kistler, type 9286) integrated on the same level. Measurement values were recorded with BioWare software. The capture rate was 1 kHz. No filtering was necessary.

The following forces were measured with a time resolution of 1 ms:

- Horizontal force in walkway direction F_x
 - Vertical force F_y
 - Horizontal force perpendicular to walkway direction F_z .
- The following requirements quotients were calculated from the forces:

- requirements quotient $Q_x = \left| \frac{F_x}{F_y} \right|$

- requirements quotient $Q_{xz} = \frac{\sqrt{F_x^2 + F_z^2}}{F_y}$

- requirements quotient $Q_z = \left| \frac{F_z}{F_y} \right|$

Recording of the heel movement

During heel strike on the force measurement platform, the heel movement was recorded with a video camera. The camera system recorded a picture frequency of 150 Hz. The time between the two pictures is 7 ms. For later motion analysis, the heel was marked (Fig. 2). The analysis of the marked points was done with Winanalyze software. The software tracked the marked points for analysis. The last three pictures before heel strike were analysed. The

Fig. 2. Recording of the heel movement during the heel strike phase.

horizontal heel strike velocity was extracted from the horizontal difference of the heel marking in the last time interval before heel strike.

The heel strike angle was extracted from the picture in the event of touchdown as the angle between the heel sole and the floor.

The extraction of the contact area is to be seen only as an estimation. The aim was to confirm the sliding areas used in the sliding friction measurement devices according to DIN 51131⁹⁾. The contact area was extracted from the video sequences too. Therefore, the pictures between the heel strike and Q_1 were analysed. The length of the heel in contact with the ground was measured in the pictures. This length was drawn as a centreline in a contour plot of the heel print. On the single points (that means at the different time points) lines were drawn orthogonal to the centreline. The areas of the heel sole between these orthogonal lines were calculated and summarised. These are the areas of the heel in contact with the floor in that time. Because of the fact that the foot in the video sequences is not parallel to the camera this only can be an estimation.

Measurement of walking velocity

The walking velocity was measured with 2 light beams at a distance of 1 m with electronic time measurement.

Test persons and footwear

For the selection of test persons, parameters like sex, age, size and weight were brought into an equal distribution. The group consisted of 22 test persons: 12 female, 10 male, aged between 27 and 59 (average 42.6, SD 10.2). For every person 8 walks were measured. Overall, 176 walks were reported. To test normal walking behaviour, the test persons wore their normal individual footwear:

- normal summer footwear but
- no boots and no sandals
- with and without heels and
- with different sole material.

Instructions for the test persons

The test persons were encouraged to walk with their normal walking speed. The persons should not walk with concentration to meet the force-plate. Therefore, the stride length was measured from every test person during preliminary walks. With this value an individual point for the start of the walkway to meet the plate was determined for every person. So the people were able to walk freely, without concentration on the platform.

Results

Forces applied to the floor

The results of the analysis of the movement path and the heel strike forces show distinctive differences. How a person places the heel on the floor is individual based on walking type. The kinematics of walking is specified by pendulum amplitude of the leg and the stride length. The flight path angle of the heel in the heel strike phase is critical. It is possible that during the contact point of the heel, there is a movement and a horizontal force F_x applied to the floor towards or opposite of the walking direction. Only when there is a positive force (towards the walking direction) applied to the floor, is there an opportunity for the heel to slip (see 'Walking process').

Depending on the direction of the force F_x , two different types (A and B) of walking were classified.

Type A is when F_x is opposite to walking direction. The horizontal velocity v_{ho} thereby is low, and the foot comes in a steep path down to the floor.

Type B is when F_x is in walking direction. V_{ho} thereby is high, and the foot comes in a flat path of movement down to the floor.

Figure 3 shows paths of movement of the rear heel edge for type A and B walkers.

The distribution of the types in the test was as follows:

- 73% are of type A,
- 27% are of type B.

It seems that the majority of people are walking type A. During a higher walking velocity, characteristics of a type A walker changed to a type B.

At the beginning of contact, half of the type A test persons had a F_x around Zero for a short time before it became a negative value (backwards). This negative value is uncritical because slipping at this value is only possible opposite to walking direction and can mostly be corrected by taking a step forward. In the middle, F_x changed into a positive value after 22 ms, and the critical phase for slipping began. Figure 4 shows an example for type A.

Figure 5 shows the calculated requirements quotients for a type A walker. As noted for the short time at the beginning and the end when the forces are around Zero,

Fig. 3. Paths of movement of the rear heel edge before heel strike of 3 test persons for type A and B.

Fig. 4. Forces applied to the floor over time example for type A walker.

Fig. 5. Requirements quotients over time example for type A walker.

Fig. 6. Forces applied to the floor over time example for type B walker.

no calculation can be done (unstable values for Q). For the time that is of interest for slipping ($F_x > 0$), there are two maxima for Q_x (Q_1 , Q_2). In the middle, the values of Q_1 and Q_2 are equal. So, the first maximum Q_1 is used for further analysis. The maximum Q_3 in the phase of lift off is uncritical because F_x is negative.

For type B F_x begins with a positive value (towards walking direction). That means that slipping can occur right after contact. Biodynamical parameters are very different from type A. Figure 6 shows an example for type B.

Figure 7 shows the distribution of $t(F_x=0)$ where F_x changes direction (for type B walkers $t=0$). The mean value for type A is 22 ms. Figure 8 shows the distribu-

tion of F_y for that time. The values $F_y=0$ are values for a type B walker. Figure 9 shows the distribution of F_y for the first maximum of the requirements quotient Q_1 . The range of F_y where slipping can occur is between $t(F_x=0)$ and $t(Q_1)$. Taking into account the maxima of these distributions the range for F_y is between 350 N and 500 N for type A walker and between 0 N and 600 N for type B walker.

Table 2 shows an overview of the measured and calculated values. The requirements quotient for the critical phase of slipping after heel strike has a value of 0.22.

Walking velocities

The mean value of the walking velocity for the 176

Fig. 7. Distribution of $t(F_x=0)$ (Point of direction change of F_x). Fig. 8. Distribution of $F_y(t(F_x=0))$. Fig. 9. Distribution of $F_y(Q_1)$.

Table 2. Overview of the measured and calculated force values for straight walking

Measured and calculated force values for straight walking		
	Mean value	SD
Q_1	0.22	0.06
$F_y(Q_1)$ [N]	493	157

Table 3. Summary of the distribution of walking velocity

walking velocity			
Mean value	SD	Minimum value	Maximum value
5.4 km/h	0.5 km/h	4.0 km/h	6.9 km/h

walks was 5.4 km/h (SD 0.5 km/h). Table 3 shows the values.

Heel strike velocities

Foot movement was recorded with a time difference of 7 ms in the video sequence pictures. Before heel strike the foot movement is nearly linear. After heel strike the linear movement changes into a rotating movement. The last three pictures before heel strike were interpreted (see

Fig. 3). Heel strike velocities are the velocities of the last time interval before heel strike. Figure 10 shows the deviation of the values.

For a type A walker the maximum of the distribution is between 0.1 and 0.3 m/s. Type B walker has a higher maximum in the distribution of heel strike velocity, between 0.7 and 0.9 m/s. Table 4 shows a summary of the values.

Area and angle for heel strike

The heel strike angles between the sole of the heel and the flooring were extracted from the video sequences. Table 5 shows the values. The mean value for all walkers is around 22°.

The contact area was analysed only during some walks. The effective contact area in the possible event of a slip depends on the heel strike angle, the elasticity and profile of the material and the weight of the person. The areas were estimated from the video sequences at the time of the maximum of the requirements quotient Q_1 .

The values are in the range of:

- 10 cm²
- < 2 cm² for hard, high heels (stiletto).

Fig. 10. Distribution of horizontal heel strike velocity v_{ho} for Type A and B.

Table 4. Summary of the distribution of horizontal heel strike velocity v_{ho} for type A and B

Type	Horizontal heel strike velocity v_{ho}		
	Maximum value of distribution	Mean value	SD
A	10 ... 30 cm/s	49.2 cm/s	46.2 cm/s
B	70 ... 90 cm/s	84.1 cm/s	40.2 cm/s

Table 5. Summary of the distribution of heel strike angles for type A and B

Type	Heel strike angle	
	Mean angle	SD
A	21.8°	4.6°
B	22.8°	5.1°
All	22.1°	4.7°

So, the critical parameter for slipping with normal footwear is a contact area of 10 cm².

Discussion

Suggested Parameters for testing device

The dynamic coefficient of friction depends mainly on the sliding velocity of the shoe and the surface pressure. Testing, therefore, should be performed for a combination of movement parameters that are realistic for human walking. Table 6 shows these suggested combinations.

Velocity

Because of the fact that the dynamic coefficient of friction depends on the velocity for visco-elastic friction^{10, 11)},

Table 6. Suggested combinations of movement parameters for testing

Type	v_R [cm/s]	F_y [N]	F_y/A [N/cm ²]	Q [-]
A	0 ... 30	350 ... 500	35 ... 50	0.22
B	70 ... 90	0 ... 600	0 ... 60	0.22

the test device should be able to measure at velocities that are realistic for human walking. Taking into account the maximum values of distribution for the two types of walkers the test device should have the following two velocities for testing:

- between 20 and 30 cm/s for type A walker (it is difficult to achieve steady sliding below 20 cm/s and the variation of measurement values for friction-coefficient is very high)
- between 70 and 90 cm/s for type B walker (or for walking with higher velocity).

Surface pressure and area of the sliders

The ranges of F_y that are of interest for both the type A (350 N–500 N) and the type B (0–600 N) walkers are very broad, and they partly have the same ranges. With respect to the contact area of the heel (10 cm²), a surface pressure between 0 and 60 N/cm² is possible for the walkers. This range is difficult to model in one device. Especially for mobile testing devices, there is a mass limitation for transport. Additionally, because of the fact that for type B walkers there are also possible low values for F_y , a value of 8 to 10 N/cm² may be a good compromise. For an area of the sliders up to 12 cm², a mass of the test device of 10 kg is acceptable for mobile use.

Table 7. Suggested dynamic coefficients of friction for the evaluation of flooring

Dynamic coefficient of friction	Comment
> 0.45	Flooring is slip resistant
0.3–0.45	Sufficient slip resistance under certain conditions of use taking into account the conditions of use of the flooring e.g. contamination, further measures to increase slip resistance may be necessary
< 0.3	Insufficient slip resistance

Slider materials

The material of the shoe soles worn by people is of great variety. These materials must be able to predict the slipperiness of a floor under different conditions, like dry or wet conditions. But this was not the task of this study. Studies about materials can be found elsewhere^{12–14}.

Suggested dynamic coefficient of friction for evaluation of the flooring

As stated for safe walking, the dynamic coefficient of friction has to have a higher value than the requirements quotient. The requirements quotient has a mean value of 0.22 (SD 0.06).

Based on the deviation of the requirements quotient, we suggest a value of dynamic coefficient of friction of 0.45 as limit for the evaluation of the slip resistance of a flooring. With a value higher than 0.45, 99.9% of the walkers are able to walk without the risk of slipping and the floor can be evaluated as slip resistant.

A value of 0.3 for the dynamic coefficient of friction means that 90% of the walkers would be able to walk without the risk of slipping. So, for the range between 0.3 and 0.45 the flooring can be evaluated as slip resistant under certain conditions of use. Further measures to increase the slip resistance of the flooring may be necessary, taking into account conditions of use, like contamination or dynamic loads of the walker.

For values of dynamic coefficient of friction below 0.3 we evaluate the flooring as not slip resistant (see Table 7).

Conclusions

The aim of this study was to derive essential parameters and their values that characterise the human walking process to use them in a mobile device to evaluate the slip resistance of flooring.

The model, we used, is the friction model between shoe and flooring. As essential parameters for the mobile testing device sliding velocity, surface pressure and area of the sliders were derived.

In DIN 51131⁹), the present standard for evaluation of slip resistance of floorings with mobile testing device, the parameter sliding velocity has a value of 0.2–0.25 m/s.

Our study shows that 27% of the walkers (type B walkers) have a higher heel strike velocity. So, the measurement procedure of the standard cannot model the critical phase for slipping for those walkers realistic. On the other hand, as reported elsewhere^{10, 11}), the dynamic coefficient of friction depends on the velocity for visco-elastic friction. A decrease of the dynamic coefficient of friction for higher sliding velocities is possible for some types of floorings. This may lead to the situation that a flooring, evaluated as slip resistant with the low sliding velocity of the standard, is not safe for type B walkers. An improvement of the standard seems to be necessary. A second sliding velocity of a higher value should be added. According to our study, a value of 0.7–0.9 m/s for this second sliding velocity is suggested to evaluate slip resistance of floorings.

Statement

Informed consent was obtained by all test persons that took part in the walking tests. The relevant standards for the tests were observed. Accordingly, the tests comply with the requirements for ergonomic research work.

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