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Safeguarding of pinch and shear points on power windows by limitation of the closing velocity: A pilot study

Hiltraut Maria Paridon *, Detlef Mewes, Fritz Mauser

Berufsgenossenschaftliches Institut Arbeit und Gesundheit, Psychology and Social Sciences,
Koenigsbruecker Landstrasse 2, 01109 Dresden, Germany

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Abstract

Power-operated windows are increasingly employed in modern buildings engineering. When they close, these windows give rise to pinching and shearing points between the window sash and the frame at which injury may occur. A number of safety measures, including reduction of the closing velocity, may be considered for minimization of the risk of injury. The purpose of the present study is to identify the closing velocity at which a person may still withdraw their hand safely from the window. The subjective stress was also measured. The deformability of the fingers was first determined. In order to measure reaction times, test apparatus was fabricated in which a vertically closing window was modelled. The reaction times and the subjective stress were measured at a number of closing velocities.

The results show that neither the reaction times, nor the subjective stress vary as a function of the closing velocity, but that the closing velocities recommended in the past are too high. A velocity of between 2.5 and 5.0 mm/s may be recommended. Reduction of the closing velocity can help to reduce the risk of injury. It should not, however, be the sole measure for enhancing the safety of power-operated windows.

Keywords: Power-operated window; Closing velocity; Subjective stress

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* Corresponding author. Tel.: +49 3514571723; fax: +49 3514571715.
E-mail address: hiltraut.paridon@hvbg.de (H.M. Paridon).

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1. Introduction

Power-operated windows are increasingly employed in modern buildings engineering. When they close automatically, these windows give rise to pinching and shearing points between the window sash and the frame. Pinching and shearing points are frequent causes of injury such as bruising, compression fractures, lacerations and occasionally even bone fractures. Injuries chiefly affect the fingers and hands (Hoffmann and Rostek, 2003).

Power-operated windows are also frequently used in automobiles. To investigate how prevalent injuries in association with motor vehicle power windows are, the National Center for Statistics and Analysis (NCSA) of the National Highway Traffic Safety Administration (US Department of Transportation) completed a study on such cases. The data show that in a 1-year period (1993–1994) an estimated 499 persons were injured in association with motor vehicle power windows and that 1.88% of them were injured as a result of (unintentionally) closing the power window. The data also show that the body part most severely injured was a finger for the majority of the persons (NCSA, 1997). Although the injuries associated with power windows are rather infrequent and their severity is mostly minor or moderate, the US Department of Transportation decided to amend the Federal Motor Vehicle Safety Standards (FMVSS) No. 118 by adding a new paragraph (S6). This paragraph specifies that switches for theses windows in new motor vehicles subject to the standard must pass an accidental actuation test that uses a test device simulating a child's knee. The agency believes that the accidental actuation test provides a simple and effective means of evaluating power window systems and will enhance the protection of people, especially children.

Considering the frequency of industrial injuries associated with power-operated windows in buildings the internal data of the German federation of institutions for statutory accident insurance and prevention show that these accidents are not very prevalent and that there are no fatalities. From 1991 to 2003 there were 471 accidents while operating at windows according to a projected statistic on the basis of 10% of all industrial accidents. Thus, accidents at power-operated windows in buildings do not play a major role. This kind of windows is, however, increasingly employed in modern buildings engineering and therefore preventive measures should be amended. For the avoidance of injuries, pinching and shearing points on moving components and machine parts must be safeguarded. A range of measures may be considered for minimization of the risk of injury on power-operated windows. These include the fitting of guards, pressure-sensitive strips, and light curtains, or limitation of the closing force to a value which is deemed safe. Besides these measures, the potential hazard may also conceivably be reduced by a reduction in the closing velocity of the window, since at a sufficiently low velocity, a person would have sufficient time to withdraw their hand from the danger zone even once contact has already been made with the window sash. A number of technical regulations state velocities of between 10 mm/s and 300 mm/s as suitable maximum values for moving components (EN 693, IEC 60335-2-103, EN 1010-1, EN 81-1, EN 81-2). These values are however generally applicable only in conjunction with other protective measures. The recommended velocities vary widely, and the closing velocity appropriate for power-operated windows is unknown. Therefore, the present study was carried out to identify a velocity at which the gap between window sash and frame may be closed which enables a person to withdraw their fingers or hand without injury. The resulting adequate velocity can be incorporated in the associated standards named above within their regular revision process. The study is further to ascertain whether differences in closing velocity are even registered by participants, and whether such differences result in different levels of stress.

Two items of information are needed for computation of the adequate velocity: first, the dimension in millimetres by which fingers can be pinched without bodily injury and second, the reaction time when the hand is pulled back from the window as it closes. With this information, the adequate velocity can be computed by the following formula: $v_{\mathrm{adeq}} = s/t$, where v_{adeq} = adequate velocity, s = finger deformability, t = reaction time, i.e. the time from contact with the window sash to exiting of the danger zone. The rationale behind this formula is the following: as soon as the closing window sash makes contact with the hand lying on the window frame, the participant begins to pull the hand back. While this reaction is being prepared, the window continues to move and begins to pinch the fingers. This is possible without adverse effect for a certain amount of time. The person must react within this time and withdraw the hand. The duration of this time span depends upon the reaction time and the deformability of the finger. If, for example, a finger can be deformed by 4 mm without injury and the reaction time is 500 ms, the adequate velocity is 8 mm/s. Conversely, if the deformability is 1 mm and the reaction time 700 ms, the adequate velocity is 1.43 mm/s. In order to determine the adequate velocity, a two-part study was conducted. In the first part the average finger deformability was measured and in the second, the average reaction time at different closing velocities. In addition to the reaction time, the study examined whether participants actually register differences in closing velocity and whether these differences lead to differences in subjective mental stress. If one velocity leads to a higher mental stress than another, this should perhaps be considered in recommendations for velocities.

2. Methodology

2.1. Procedure

The study consisted of two parts. First, the forefinger, middle finger, and ring finger of 12 participants were measured in order to determine the deformability of the fingers. The thumb and little finger were not measured, as they are not at risk of contusion while the hand is lying between window sash and frame. The middle of the phalanxes and the knucklebone were measured twice on each finger by means of a calliper gauge: once without deformation and once with the maximum possible deformation without injury to the finger (see Fig. 1 for the different measuring points). In order not to harm participants, they were asked to indicate when their threshold of pain was reached while the jaws of the calliper gauge were pushed together.

In the second part, reaction times and subjective assessments were determined. The reactions were tested at three different closing velocities (500 mm/min, 750 mm/min, and 1000 mm/min). The participants were instructed to remove their rings, to place their right hands on the window frame and to withdraw them as soon as they registered contact with the closing window sash. In order to ensure that the participants withdrew their hands only in response to tactile feedback and not to visual stimuli, they were instructed to position themselves laterally to the window (Fig. 2 shows the hand position).

The reaction time was measured five times at each velocity, the first trial being considered as practice. Order of velocities was balanced over participants according to a Latin square. Based upon the assumption that in a real-life environment, a person's attention is

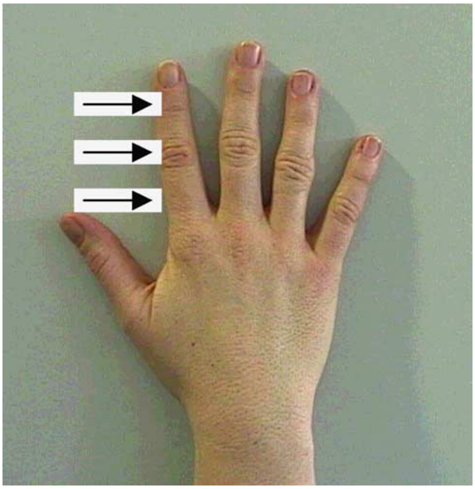

Fig. 1. Measuring points for the forefinger, middle finger and ring finger.

Fig. 2. Positioning of the hand between window sash and window frame.

not focussed upon his or her fingers when they are resting on a window frame, but is more likely to be distracted for instance by a conversation with a colleague, reaction times were measured under two conditions: with and without distraction. The distraction was achieved by means of shadowing, i.e. the participants were required to repeat a text played to them over headphones. The conditions were counterbalanced across the participants, i.e. half of the participants began with the distraction condition, the other half with the non-distraction condition. The subjective mental stress was quantified on a simple sliding scale. The participant was required to indicate on the scale his or her perceived stress immediately upon completion of the five trials at a given velocity. The participants were able to select a desired point on the scale between no stress, low stress and severe stress. A corresponding numeric value ranging from 0 to 100 can be read off the back of the scale (for a detailed description see Windemuth et al., 2001). Upon completion of the first three blocks, i.e. once the participants had experienced the different closing velocities either with or without distraction, they were required to complete a questionnaire. The participants were asked whether they had observed any change in the course of the experiments and if so, what kind of change. The purpose here was to establish whether the participants had registered the differences in velocity. Next, they were asked directly whether the closing velocity had changed and if so, to select from a number of velocities (from 2 to 6).

2.2. Materials

For the first part of the study, a standard calliper gauge was used. For the second part, test apparatus constituting a model of a vertically closing window was developed and built (see Figs. 3 and 4). The window sash and frame sections were modelled by suitably formed high-grade steel sheet. The window sash was connected by cable and roller to the crosshead of a universal materials testing machine, the controller of which was used to select a constant closing velocity. For safety reasons, the effective dead weight of the window sash was limited by counterweights such that a force of not more than 12 N was able to act upon the hands during the closing operation. According to Mewes and Mauser (2003) at this low force no adverse effects on well-being or even pain are to be expected.

A start and a stop pulse were defined for measurement of the reaction time. For generation of the start pulse, the window sash section and frame section were designed to act as a contact sensor by way of continuous measurement of the resistance between the two sections. A trigger sensitivity of 100 MΩ was selected. As soon as the sash section made contact with a hand resting upon the frame section, the resistance dropped. This drop in

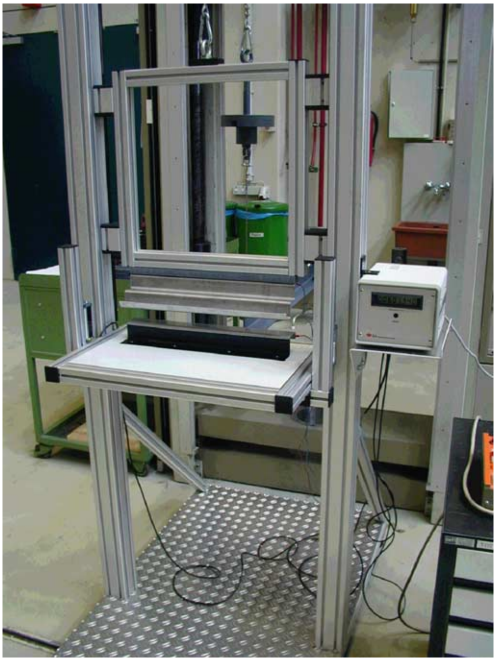

Fig. 3. Test bench.

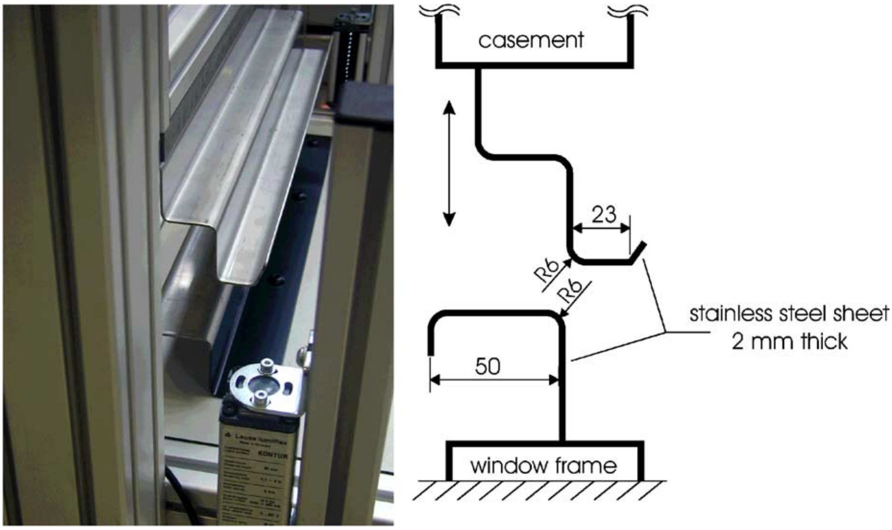

Fig. 4. Window sash and frame sections.

resistance served as the start pulse. The stop pulse, transmitted upon withdrawal of the hand from the hazard area, was detected by a light curtain (detection field: 80 mm; vertical resolution: 5 mm; duration of signal: <1 ms). The light curtain was located 1 cm behind the window sections, thus ensuring that the hazard area had been safely exited. A high-resolution (1 μs) stopwatch was employed for timing.

To create a distraction, a passage from a simple German novel was read aloud by the experimenter and recorded on a CD. This was played back to the participants over standard earphones. A simple sliding scale was used to measure the mental stress.

2.3. Participants

The finger deformability of the right hand of 6 female and 6 male participants was determined. All participants were right-handed. They were aged 23–54 years (mean age 39.7 years). Eighteen right-handed participants (9 male and 9 female) took part in the second part of the study. They were aged 26–62 years (mean age 43.1 years) and either had an academical or a clerical occupation in a research institute.

3. Results

3.1. Finger deformability

Table 1 shows the average deformability of the forefinger, the middle finger, and the ring finger measured at the upper and lower phalanx and at the knucklebone.

As was to be expected, the lower phalanx can be pinched most readily without injury (3.21 ± 1.3 mm), the knucklebone least readily (1.43 ± 0.7 mm). Averaged over all data, the deformability was 2.26 ± 1.2 mm. As can be seen from the data the variability of the deformability is quite considerable.

Table 1
Average finger deformability of the forefinger, the middle finger and the ring finger for the upper and lower phalanx and the knucklebone

	Average finger deformability in mm with standard deviation		
	Forefinger	Middle finger	Ring finger
Upper phalanx	2.3 ± 0.9	2.0 ± 1.1	2.2 ± 1.0
Lower phalanx	3.2 ± 1.5	3.3 ± 1.3	3.1 ± 1.3
Knucklebone	1.6 ± 0.6	1.4 ± 0.9	1.3 ± 0.4

3.2. Reaction times

Mean reaction times and the corresponding standard deviations for the two conditions (with and without distraction) and for the three velocities are shown in Table 2. Fig. 5 shows the distribution of the mean reaction times for each participant and the overall means at the different conditions. The first trial at each velocity was ignored for the purpose of data analysis. As the data show, the reaction time was higher at all velocities under the condition with distraction than under the condition without distraction. Analysis of variance (ANOVA) revealed a strong effect of distraction upon RT, ($F_{(6,102)} = 19.16$, $p < .000$). Compared to that for a velocity of 750 mm/min, mean RT was higher at velocities of 500 mm/min and 1000 mm/min. But neither a significant main effect of velocity ($F < 1$) nor a significant interaction between velocity and distraction ($F < 1$) were observed. The absence of such an interaction permits the assumption that the participants' attention was

Table 2
Mean reaction times (RT) at the different closing velocities for the two conditions, without and with distraction

Velocity in mm/min	RT and standard deviation in ms without distraction	RT and standard deviation in ms with distraction
500	337 ± 115	506 ± 285
750	297 ± 79	430 ± 154
1000	312 ± 100	460 ± 234

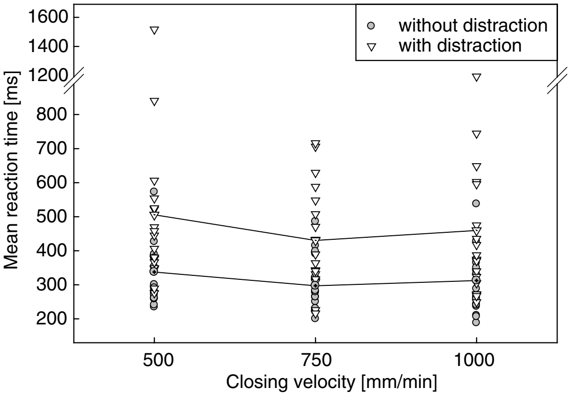

Fig. 5. Distribution of the mean reaction times for all participants and the overall means at the different closing velocities for the two conditions, without and with distraction.

distracted to the same degree at all velocities. The average RT with distraction was 465 ms and without distraction 315 ms.

3.3. Adequate velocity

As already illustrated, the adequate velocity can be computed by $v_{\mathrm{adeq}} = s/t$, where v_{adeq} = adequate velocity, s = finger deformability, t = reaction time. It is, however, not possible to determine a clear-cut velocity, since the velocity depends upon the values selected. The following calculation demonstrates this. The slowest average RT with distraction and the average deformability of the knucklebone yields the following velocity results: $v_{\mathrm{adeq}} = 1.43\,\mathrm{mm}/0.506\,\mathrm{s} = 2.83\,\mathrm{mm/s}$ (169.6 mm/min). The average RT with distraction and the deformability averaged over all data yields the following velocity results: $v_{\mathrm{adeq}} = 2.26\,\mathrm{mm}/0.465\,\mathrm{s} = 4.86\,\mathrm{mm/s}$ (291.61 mm/min).

Depending upon the values chosen, the adequate velocity lies between 2.5 and 5.0 mm/s. Independent of the chosen values the resulting adequate velocities are substantially lower than the velocities which have been recommended up to now.

3.4. Subjective mental stress

The average subjective mental stress and the corresponding standard deviations at the different velocities for the two conditions, i.e. without and with distraction, is shown in Fig. 6. As with the reaction time, subjective stress was higher when the participants were distracted than without distraction. ANOVA revealed a strong effect of distraction upon subjective stress, ($F_{(6,102)} = 24.0$, $p < .000$). The stress increased with velocity, but neither a significant main effect of velocity ($F_{(6,102)} = 1.35$, $p = 0.26$) nor a significant interaction ($F < 1$) was observed. It can be concluded that the closing velocity did not affect subjective mental stress.

3.5. Questionnaire data

Participants were first asked whether they had observed any changes in the course of the experiment. Half of the participants had not observed any change. The changes observed

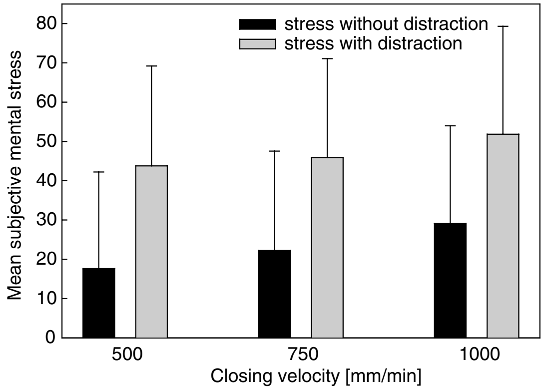

Fig. 6. Average subjective mental stress and standard deviation at the different velocities for the two conditions, without and with distraction.

by the other half are presented in Fig. 7. One person in each case indicated that the sound level and the pressure of the closing window had changed. Two persons responded that they sensed contact with the closing window at an earlier point. It may be assumed that these participants, with the exception of the one who mentioned the sound level, actually observed the different velocities, but expressed it different ways, i.e. in terms of different pressure or contact times. Five participants responded that they had observed different closing velocities.

The participants were next asked directly whether they had observed different closing velocities and if so, how many. The assumptions of the participants regarding the number of velocities are shown in Fig. 8. Seven participants responded that they had not observed changes in the velocity, i.e. they assumed one velocity. Three participants indicated 2 velocities, 7 participants 3 velocities and 1 participant 4 velocities. Less than half of the participants were therefore able to state the actual number of velocities. It can be concluded not only that different closing velocities lead to the same level of mental stress, but that they are not even registered correctly by most participants.

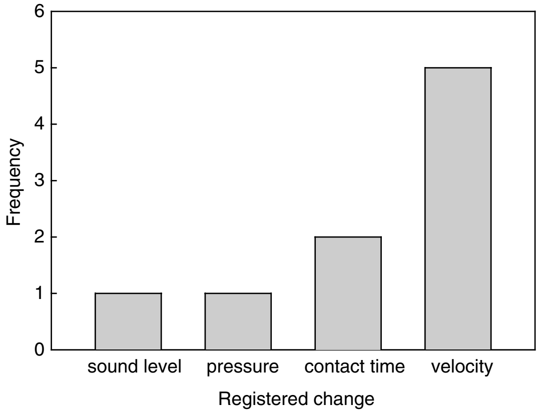

Fig. 7. Frequencies of the registered changes during the experiment.

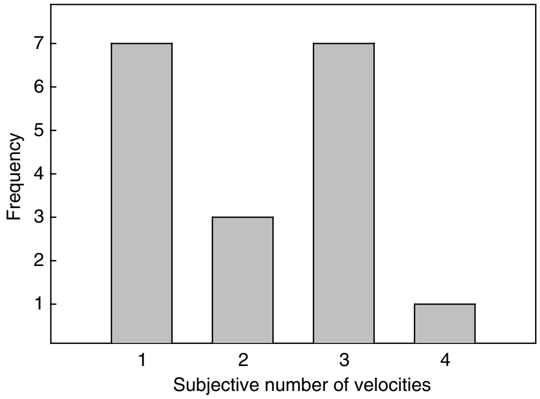

Fig. 8. Frequencies of the subjective number of closing velocities.

4. Discussion

The present study investigated the adequate closing velocity for power-operated windows. Two forms of information were required and therefore measured: the average deformability of the forefinger, middle finger and ring finger, and the average reaction time for withdrawal of the hand from the window as it closed. The reaction time was measured under different closing velocities and both with and without distraction. Besides finger deformability and reaction time, the subjective mental stress was assessed, as was the participants' awareness of the different closing velocities. Finger deformability was highest at the lower phalanx and lowest at the knucklebone. The reaction time was significantly higher under the condition with distraction than without distraction. Closing velocity did not have a significant effect upon reaction time. Adequate velocity was computed by the following formula: $v_{\mathrm{adeq}} = s/t$, where v_{adeq} = adequate velocity, s = finger deformability, t = reaction time, i.e. the time from contact with the window sash to exiting of the danger zone. Depending upon the values selected, a velocity of between 2.5 and 5.0 mm/s can be recommended. Thus, the closing velocities recommended in the past are too high and they should be reduced. All the more, because the variability of the deformability is substantial and there are people with only little deformability. Nevertheless, reduction of the closing velocity should not be the sole measure for enhancing the safety of power-operated windows.

Furthermore, there is still a number of questions that should be considered in further research (see below) and due to the small number of participants, the conclusions should be interpreted cautiously.

Like the reaction time, the subjective stress was higher under the distraction condition than under the non-distraction condition, but did not vary significantly according to the velocity. Interestingly, only half of the participants were aware that the closing velocity had changed during the experiment, and less than half were able to state the actual number of velocities. The results suggest that the subjective perception can be ignored during calculation of the adequate closing velocity of power-operated windows.

The present study was a preliminary attempt to determine an adequate closing velocity for power-operated windows. Certain aspects were not considered, and could be included in further studies. First, the reaction time of children and of elderly people was not studied; these may differ from those of middle-aged adults. Second, the participants were instructed to remove their rings. If worn, a ring may result in the hand being trapped between the window sash and the frame. Further aspects worthy of consideration include the precise positioning of the hand and the occupation of the participants. As described above the participants either had an academical or a clerical occupation. For actual blue-collar workers, fingers may be more resistive to pressures due to the effect of prolonged manual work in skin, which may affect the reaction time. If reaction time behaviour depends on the type of work experience a person has, might also be subject of further research. Also the effect of other environmental distractions, e.g. sunshine, could be studied.

To summarize, the results of the present study show that the closing velocity of power-operated windows should be lower than that recommended to date. Nevertheless, this form of safety measure should not be the only one taken to increase safety. Another possible measure is the limitation of forces. The reduction of the closing velocity is, however one means of hazard reduction.

References

EN 693, 2001. Machine Tools—Safety. Hydraulic presses.

EN 1010-1, 2004. Safety of machinery—Safety requirements for the design and construction of printing and paper converting machines. Part 1: Common requirements.

EN 81, 2004. Safety rules for the construction and installation of lifts. Part 1: Electric lifts, Part 2: Hydraulic lifts.

Hoffmann, B., Rostek, R., 2003. Arbeitsunfallstatistik [Occupational accident statistics] BGZ-Report 3/2003. Hauptverband der gewerblichen Berufsgenossenschaften (HVBG), Sankt Augustin.

IEC 60335-2-103, 2003. Household and similar electric appliances—Safety. Part 2—103: Particular requirements for drives for gates, doors and windows.

Mewes, D., Mauser, F., 2003. Safeguarding crushing points by limitation of forces. Int. J. Occup. Safe. Ergonom. 9, 177–191.

National Center for Statistics and Analysis, 1997. Injuries associated with hazards involving motor vehicle power windows. Research Note. Available from: <http://www-nrd.nhtsa.dot.gov/pdf/nrd-30/NCSA/RNotes/1997/rn_windo.pdf>.

Windemuth, D., Müller-Gethmann, H., Bindzius, F., Eckhardt, G., 2001. Die Stresskammer—ein mobiler Arbeitsplatz zur Verdeutlichung psychischer Belastungen und Beanspruchungen. Die BG 10, 520–523.