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Perceived safety and biomechanical stress to the lower limbs when stepping down from fire fighting vehicles

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Abstract

Injuries related to emergency vehicles represent 19% of compensated work accidents for fire fighters, 37% of which occur while stepping down from their vehicles. This study compared the impact forces, the use of upper limbs and the perception of danger of fire fighters as they step down from five different locations on fire trucks. The results show that stepping down from the crew cab facing the street produces impact forces averaging 3.2 times the subject's body weight, but is also perceived as the safest way to descend in one of the two groups of fire fighters that participated in the study. Stepping down from the same location, but facing the truck, produced significantly less impact force and a better distribution of the energy over time. This may be achieved through better control of the descending leg, ankle flexion, and the use of grab bars. A re-design of the access to emergency vehicles should take into account both the safety needs and reduction in biomechanical stress of fire fighters.

Keywords: Fire fighters; Emergency vehicles; Ingress/egress; Safety; Biomechanical stress

1. Introduction

Fire fighting vehicles are built to ensure a quick delivery of personnel, material and water in order to rescue victims and extinguish fires. Their design is governed by performance and regulated by standards (NFPA, 1999; ULC, 1996) that state, for example, a minimum ground clearance of 20 cm, and a minimum of 1125 l of water to be carried in a pumper. Measurements (Tables 1 and 2) conducted for the preparation of the current study, reveal that the drivers' cabs and crew cabs are generally 1 m above ground, and the height of the first step is on average 50.1 cm above the ground. The height of side and rear running boards is between 49.3 and 53.4 cm above the ground. The distance from the ground to equipment on the roof top, or to aerial ladders or gondolas, varies between 174 and 308.6 cm, depending on the type of vehicle. There can be as many as seven retractable or fixed footholds or steps to reach the equipment, with uneven horizontal and vertical spacing and alignment. Upon arriving at an emergency scene, fire fighters will step down from the crew cab wearing their turn-out gear. Crew and vehicles typically answer 20,612 calls a year for a city of 1 million inhabitants, resulting in 59,303 vehicle outings (SPIM, 1993).

Following a request from a joint occupational health and safety association (APSAM, 1994), a detailed analysis by one of the authors of 517 accidents reported

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Table 1
Heights of different parts of fire fighting vehicles, in cm from the ground

	Driver's cab	Crew cab	Roof or equipment	Lateral running board	Rear running board
Average height from ground	100.7	103.2	211.3	49.3	53.37
Standard deviation	22.94	6.49	45.18	5.23	4.06
Range	41.0–139.8	95.0–111.0	113.0–308.6	43–54.6	47.0–60.0
Sample number	13	9	13	5	8
Number of steps available (range)	1–3	1–3	1–7	—	—

Table 2
Heights to the first reachable step of fire fighting vehicles, in cm from the ground

	Driver's cab	Crew cab	Roof or equipment
Average height from ground to first step	50.1	44.4	50.7
Standard deviation	8.16	10.98	7.88
Range	35.0–61.5	30.0–58.0	28.0–60.0
Sample number	13	9	13

in a previous study (Champoux and Cloutier, 1996) was made. It was found that emergency vehicles were either causal or accessory in 19.5% of all the reported occupational injuries in the first 6 months of 1992. Of this percentage, sprains represented 13% of the injuries when stepping up into the vehicle, while 37% occurred when stepping down from the vehicle. Stepping down from the vehicle can be done "Facing the Street", although the recommended procedure is to step down "Facing the Truck", using three points of contact (Hemmings, 1974).

Stress on the lower limbs has been studied extensively for sports activities. The force of impact of a foot touching the ground when walking can be as much as 1.5 times the weight of the body (BW), and be as much as 3–5 times the weight of the body when running (Nigg et al., 1981). During long jumps, impact forces have been reported as being as high as 8.3 times BW (Nigg, 1985). Even if the impact forces dissipate when propagating within human bones, muscles and joints, they can still reach large values when the joints of the receiving leg are locked in place, such as when going down a steep flight of stairs. Factors reported as influencing the ground impact forces are the speed of the foot, its frontal and sagittal angle on the receiving surface, the absorption of energy by the muscular system, the nature and pattern of the shoe sole, and the stiffness and quality of the contact surface (Nigg et al., 1987).

Patenaude et al. (2001) studied the impact forces on truck drivers ($n = 10$) when they stepped down from two different types of truck cabs, and reported values ranging from 1.36 to 2.16 BW. The distances above ground of the first step for these trucks were 53.5 and 41.5 cm. In contrast to fire fighters, these subjects were not wearing any special protective clothing or equipment. Some of the factors reported as influencing the results in that study were the design of the truck cab, in particular the presence or absence of handholds and grab bars, and the method used to descend, either "Facing the Truck" or "Facing the Street".

Impact forces on the feet touching the ground were also measured experimentally ($n = 10$) by Fathallah and Cotnam (2000) for subjects descending or jumping from different locations on commercially available trucks. They measured values up to 7.1 BW for subjects jumping off a cab-over-engine (COE) truck cab (125 cm off the ground), and 1.4 times BW for subjects when jumping from the first step of the same cab to the ground (43 cm high). Also, stepping down from a "step van" (43 cm off the ground) without using handles and grab bars, as if carrying a package, produced values 3.5 times the BW, but 1.9 BW for the same location using the installed handholds.

Presumably, for fire fighters, the distance to the ground from the vehicle's step or running board, the nature and quality of the ground surface, the additional weight of protective equipment, the frequency of vehicle outings, and the method used for stepping down, are all factors that could help explain the frequency of sprains when stepping down from a fire fighting vehicle. The objective of the study was to investigate the possible contribution of impact forces on the ground and biomechanical stress on the lower limbs of fire fighters wearing their turn-out gear, when they stepped down from various parts of their emergency vehicles. The perception of danger related to the methods of descent was also measured. Our hypothesis was that the magnitude of ground impact forces measured when firefighters stepped down from their fire fighting vehicles were at least similar to values measured when descending from other heavy goods vehicles. Also, it was expected that descents "Facing the truck" would generate less ground impact forces than "Facing the street", and be perceived as less dangerous.

2. Methodology

2.1. Steering committee

This study was conducted in collaboration with a steering committee that included representatives from fire departments' management and unions, from part-time fire fighters associations and from a representative of the joint Occupational health and safety (OHS) committee for municipalities (APSAM). The role of this committee was to help in identifying potentially hazardous situations, to recruit fire station management and personnel for field measurements and to validate the results in the scope of forthcoming recommendations.

2.2. Subjects

Two series of measurements were done in two different fire stations. For the group in station "A", ten male fire fighters working regularly and full-time were recruited by the officer in charge from among the fire fighters registered for the day shift. Their average age was 31.6 years ($\pm$5.9) and their average weight was 83.14 kg ($\pm$8.69) in station clothing. Fire fighting clothing consists of a two-piece fireproof suit including pants and coat, boots and safety helmet, a self-contained breathing apparatus (SCBA, with the cylinder of compressed air, regulator and mask), a temperature sensor with alarm, as well as an axe. Since that in station "A" the SCBA were stored within the backrest of the seats in the crew cab, the fire fighters stepped down the vehicle with their SCBA already buckled on their back. The average weight of this equipment was 24.5 kg ($\pm$2.3) for $n = 8$; two of the participating fire fighters were excluded from the calculation since they wore different equipment because of their role in the team. The weight of the fire clothing was obtained by subtracting the weight of the subject in fire clothing from the weight of the same individual without fire clothing. The values obtained were validated from weights specified in equipment catalogues and by weighing some equipment on site.

The group from station "B" consisted of eight male volunteer fire fighters associated with the station of a municipality with fewer than 70,000 residents. The data were collected between 7 and 10:30 p.m. on a weekday evening that coincided with their regular practice session. The average age was 38.4 years ($\pm$11.2) and average weight was 93.2 kg ($\pm$9.3) without protective clothing. The average weight of the fire fighting suit worn by these subjects during these measurements was 9.7 kg ($\pm$1.7). The difference between this value and the one calculated for group "A" is explained by the fact that firefighters in station "B" usually don their SCBA after stepping down from their vehicle because these are stored in the truck's exterior compartments.

2.3. Material and conditions

In station "A", the emergency vehicle used was an elevating platform (1990) equipped with a crew cab. The impact on the ground was measured when stepping down from the crew cab and access ladder to the platform. All measurements were taken the same day. Each subject stepped down from the crew cab four times, namely twice "Facing the Street" (condition "CREW-FS", height = 58 cm, $n = 10$ subjects) as illustrated in Fig. 1, and twice "Facing the Truck" (condition "CREW-FT", height = 58 cm, $n = 10$ subjects) as illustrated in Fig. 2. Stepping down from the ladder from the roof was done once without using the retractable step (condition "ROOF-HI", height = 56 cm, $n = 7$) and once again with (condition "ROOF-LO", height = 28 cm, $n = 7$). Fig. 3 shows the "ROOF-HI"

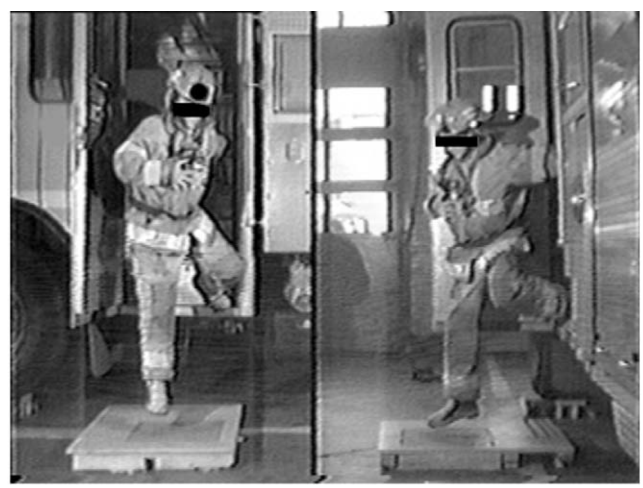

Fig. 1. Stepping down from the crew cab "Facing the Street" (CREW-FS) in fire station "A".

Fig. 2. Stepping down from the crew cab "Facing the Truck" (CREW-FT) in fire station "A".

Fig. 3. Stepping down from the roof access ladder without the retractable footstep (ROOF-HI) in fire station "A".

Fig. 4. Stepping down from the driver's cab, passenger side, of the pumper in fire station "B" (PCAB-FS).

condition. To come down from the roof, the fire fighters descend "Facing the Truck" because it is practically impossible to descend any other way because of the ladder's configuration.

In station "B", two emergency vehicles were used, namely a pumper (1966) with a cab over engine and a tanker (1996). The impact on the ground was measured at the rear running board and the driver's cab on the passenger side of the pumper, and the rear platform of the tanker. Each subject performed two step-downs for each condition. The subjects first stepped down from the driver's cab (passenger side) of the pumper "Facing the Street" (condition "PCAB-FS", floor height = 76.25 cm, $n = 8$) as illustrated in Fig. 4. The other conditions were performed from the pumper's rear platform "Facing the Street" (condition "PRUNR-FS", height = 50.8 cm, $n = 8$), then "Facing the Truck" (condition "PRUNR-FT", height = 50.8 cm, $n = 8$) as illustrated in Figs. 5 and 6. Finally, on the tanker, the subjects stepped down from the step of the rear platform "Facing the Truck" (condition "TLAD-FT", height = 45.75 cm, $n = 8$); the platform was located 85 cm from the ground (Fig. 7).

The vertical impact forces on the ground were measured with a force platform (AMTI S6A6-4) measuring 46.4 cm × 50.8 cm and bolted to a steel plate. The platform was installed near the emergency vehicle in a place where the subjects were most likely to touch ground. Since the platform and steel plate together were 10.26 cm thick, the vehicle had to be raised accordingly in order to maintain the same distance from the ground. This was achieved by driving the vehicle up 10.26-cm-thick custom built wooden ramps for all the sets of wheels as seen in Fig. 8 in fire station "B". The research team then proceeded to position the force platform on the station's concrete floor, opposite where the fire fighters normally touched ground when they stepped down; this initial position was then precisely adjusted by

Fig. 5. Stepping down from the pumper's rear running board "Facing the Street" in fire station "B". (PRUNR-FS).

Fig. 6. Stepping down from the pumper's rear running board "Facing the Truck" in fire station "B" (PRUNR-FT).

Fig. 7. Stepping down from the water tanker's rear ladder "Facing the Truck" in fire station "B" (TLAD-FT).

Fig. 8. Vertical impact force measurement set-up in fire station "B": the pumper is driven up on wooden ramps having the same height as the force platform, seen here embedded in a false floor.

doing step-down tests (without measurements) until the optimal position was found. The false floor was finally installed around the force platform by passing the connecting wires under the false floor. This prior exercise also allowed optimal positioning of the two video cameras, one in the sagittal plane and the other in the frontal plane of descent; their respective signals were mixed in the form of a mosaic before being recorded on a tape recorder. Before taking any measurements, and without any force being applied on the platform, the base value was set at zero by adjusting the resistance bridges of its control box. The platform was then calibrated by placing two 250-N weights on it; this allowed the analogue data (Volts) from the force platform to be converted into kinetic data (Newtons). The analogue output from the platform's control box was then connected to an analogue-digital converter clocked at 1000 Hz (Data Shuffle Express) with a 100 Hz low-pass filter (Lafortune et al., 1995). Finally, the latter was connected to a laptop computer that controlled the converter and stored the data. This procedure was repeated each time that the platform was moved from one measuring point to another.

2.4. Variables

Three types of variables were used: vertical impact forces, level of perceived danger, and the use of hands and feet while descending.

The vertical impact force F_z, the mediolateral impact force F_x, and the anteroposterior impact force F_y were measured. Several variables were also calculated from the force platform's basic data: sagittal and frontal resultant impact forces, time-to-peak and the theta angle of the foot on the platform's surface. However, the results obtained from these other variables are not presented here since the horizontal forces were negligible compared to the vertical force in all of the conditions of descent.

All the forces presented in this study are expressed relative to the subject's own body weight; thus, if a fire fighter weighing 686.7 N produced a ground impact force of 1716.75 N, the force on the platform is said to be 2.5 BW (1716.75 N/686.7 N = 2.5 BW), meaning that the ground impact for this fire fighter was 2.5 times his own weight without turn-out gear.

The perception of danger was measured using a series of statements ranging from "I feel extremely safe" for a score of one, to "I feel that I am in extreme danger" for a score of 10. These ranked statements were presented on a board and the subjects were instructed to point at the statement that corresponded best to their perceived level of danger, and not to say it aloud. The score corresponding to the statement was noted by a member of the research team.

The position and use of hands and feet during the descents were analyzed a posteriori using a simple observation grid on the video material recorded on location.

2.5. Experimental procedure

The following procedure was used in both fire stations. First, a representative of the research team reminded the personnel on site about the objectives of the study using a document that had been sent to the station beforehand, and answered the participants' questions. He checked the availability of the emergency vehicle or vehicles and the fire fighters who had volunteered to participate in the measurements. Finally, the research team agreed with the officer in charge about the details of the procedure to be followed in the event of an emergency call.

All the participating fire fighters were weighed in station uniform (shirt, pants and shoes), and then weighed again wearing their fire fighting clothing and their usual equipment. Each one was also assigned a number in sequence as they arrived at the truck for the trials. The subjects were all familiar with the task and the vehicles and no randomization was used since no learning effect was apprehended.

For the measurements, the fire fighters lined up in sequence according to their numbers. The first fire fighter then went to the initial step-down position and waited for the signal from the research team. A number was entered on a small panel, corresponding to the condition studied as well as the number of the first fire fighter to step down, while ensuring that the information could be seen during the video recording. At the signal, the video and data recording were started, and the first fire fighter followed the instructions, stepping down onto the force platform, stepping off the false floor, and then giving his evaluation about the safety of the task. The sequential number of the subject on the panel was then increased by one and the second fire fighter was then asked to step down. Since the protocol consisted of two measurements per fire fighter per condition, the fire fighters who had just stepped down went to the back of the line for their second test while maintaining the sequential order assigned. Once the last fire fighter has stepped down, the video and data recording were stopped and saved. For this part of the study, an audio-visual technician assisted in taking the pictures and recording the video.

2.6. Statistical analysis

One-way ANOVA was first used to test the main effects of the independent variables. However, the use of analysis of variance assumes normality of the data distribution. If this condition is met for several of the variables, the different normality tests[1] of the "Number Cruncher Statistical System" (NCSS) (Hintze, 2001) give inconsistent results for some of them. Thus, the distribution conformity hypothesis is accepted in some cases, while in others, it is accepted by one or more tests but rejected by others. Kruskal–Wallis ANOVA was chosen because its use is independent of the data distribution mode, and it applies to the median value for the data (instead of the mean value). This analysis was first used to verify whether the median value of a variable was different from the median of at least one other variable in the group. In such a case, a post hoc comparison was done with a multiple comparison test (Kruskal-Wallis Multiple Comparison Z-Value Test with the Bonferoni test) in order to identify which median was different from one or more medians in the other groups. The statistical calculations were done using the NCSS software with an α error level of 0.05 ($p<0.05$) for all the tests.

[1]The different normality of distribution tests offered by the NCSS in its module of descriptive statistics are: Shapiro–Wilk, Anderson–Darling, Martinez–Iglewicz, Kolmogorov–Smirnov as well as the Agostino kurtosis and skewness tests.

3. Results

3.1. Impact forces

For fire station "A", analysis of the vertical impact force data (Fig. 9) shows that stepping down from the crew cab "Facing the Street" (CREW-FS) resulted in the largest ground reaction, with an average value of 3.6 times the BW for subjects in plain clothes. The values obtained for the other conditions, stepping down from the crew cab "Facing the Truck" (CREW-FT) and from the roof access ladder (ROOF-HI and ROOF-LO), were all lower and differed significantly ($F_{(1.4)} = 6.95$, $p<0.001$). For these conditions, the factors that can affect the magnitude of the ground reaction were the vertical free-fall distance, the contribution of hand support, and the energy absorption role of the lower limb muscles. The lower values recorded when descending from the roof access ladder (ROOF-HI and ROOF-LO) can be explained by the fact that this descent was always done "Facing the Truck" and that it was always performed with hands on a grab bar.

For fire station "B", the two conditions in which the subjects stepped down "Facing the Street" (conditions "PCAB-FS" and "PRUNR-FS") lead to the largest impact forces (Fig. 10). Analysis of variance shows in fact that there is at least one condition that is significantly different from the others ($F_{(1.3)} = 18.40$; $p<0.001$) for the vertical axis. Two-by-two comparison of the conditions clearly shows that the two conditions in which the subjects stepped down "Facing the Street" differ from the two other conditions in which step-down is done "Facing the Truck". The other step-down condition with a large impact force (3.05 times the body weight) was found in descent from the pumper's rear platform with the use of the "Facing the Street"

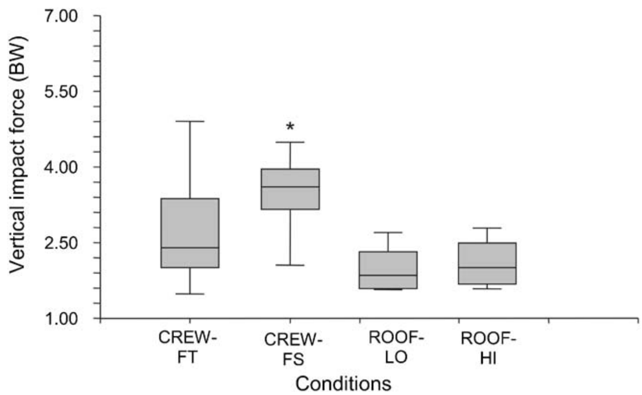

Fig. 9. Box and whiskers plot of the vertical ground reaction forces for each descent condition in fire station "A". (* denotes a condition that is significantly different for $\alpha = 0.05$).

Table 3
Frequency counts of the use of hands when stepping down from the crew cab in fire station "A"

Hand conditions		"Face the Street"	"Face the Truck"
Left hand	Tool or object	11	11
	Grab bar	2	1
	Handle	0	5
	Free	7	3
	Total	20	20
Right hand	Tool or object	7	5
	Grab bar	0	12
	Handle	6	2
	Free	7	1
	Total	20	20

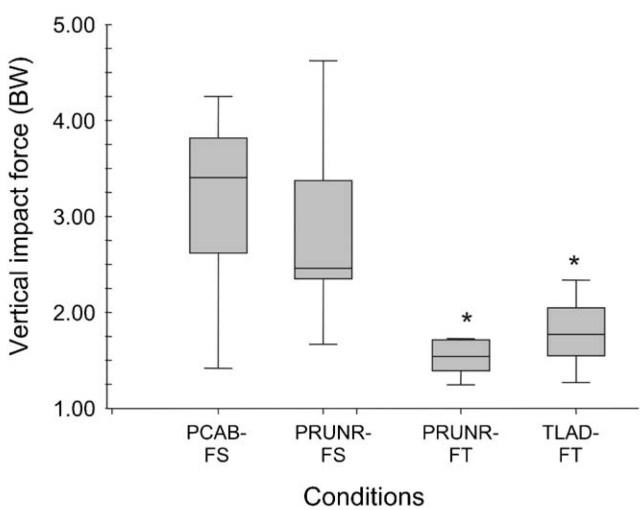

Fig. 10. Box and whiskers plot of the vertical ground reaction forces for each descent condition in fire station "B". (*denotes conditions that are significantly different for $\alpha = 0.05$).

technique (condition "PRUNR-FS"). For the conditions in which the fire fighters used a "Facing the Truck" technique (conditions "PRUNR-FT" (see Fig. 6) and "TLAD-FT" (see Fig. 7), the results showed a large reduction in the impact forces (between 1.6 and 1.85 times the body weight).

3.2. Video observations

This analysis was done only for fire station "A". For all the descent conditions combined, the subject's right foot touched the force platform first in 61.4% of the cases. The right foot touched the ground first in 77.5% of the cases in descending from the crew cab under both conditions, but the left foot was preferred when descending from the roof ladder, with the right foot touching the platform first in only 28.6% of the observed cases. In six of the 57 trials, the subject jumped on the force platform with both feet simultaneously.

The use of hands to control the descent from the crew cab was modulated by the presence of a grab bar on the right side of the cab and by a handle attached to the open door of the cab, on the left. The use of these hand supports was itself modulated by the availability of the hands; depending on their function in the team, eight out of the ten subjects carried an axe, while two others carried or held their mask or helmet in either of their hands while descending. Table 3 summarizes the use of hands while stepping down from the crew cab. The use of the door handle and grab bar was observed more often in the "Facing the truck" condition. A χ^2 comparison tested the similarity of the ratios of hand use between the two conditions. The null hypothesis was rejected for the right hand ($\chi^2 = 18.3$ for $p = 0.05$ and 3 df). Stepping out of the crew cab was the only condition in which the subjects carried a tool in one of their hands during descent.

3.3. Level of danger questionnaire

For fire station "A", Fig. 11 shows the distribution of answers on the psychophysical scale for each of the descent conditions. Scores are highest and statistically different ($F_{(1.4)} = 8.96$, $p < 0.001$) for the CREW-FT condition, meaning that the subjects reported feeling "not very safe" when descending from the crew cab "Facing the Truck" more than for any of the other conditions.

For fire station "B", analysis of variance for danger perception shows that at least one condition is significantly different from the others (Fig. 12), ($F_{(1.3)} = 2.86$; $p = 0.045$). Two-by-two comparison of

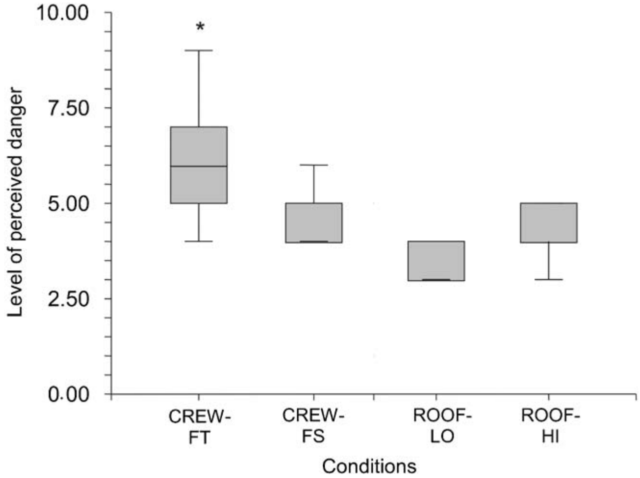

Fig. 11. Box and whiskers plot of the level of perceived danger for each descent condition in fire station "A", where 10 denotes a feeling of being in danger. (*denotes a condition that is significantly different from the others for $\alpha = 0.05$).

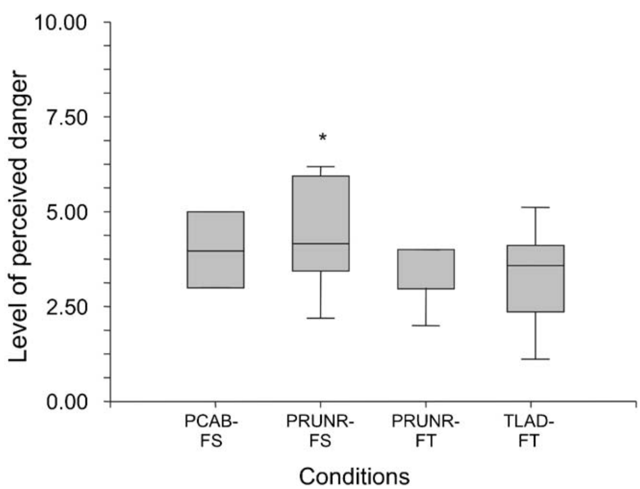

Fig. 12. Box and whiskers plot of the level of perceived danger for each descent condition in fire station "B", where 10 denotes a feeling of being in danger (*denotes a condition that is significantly different from TLAD-FT for $\alpha = 0.05$).

the descents shows that stepping down from the tanker and the pumper's running board "Facing the Truck" was perceived as being "less dangerous" than stepping down from the pumper's running board "Facing the Street". The magnitude of the impact resulting from descents "Facing the Street" therefore seemed to be considered as being a major factor that can affect the safety of fire fighters from station "B" when stepping down from a truck, in contrast to station "A", where seeing surrounding traffic is considered as being the most important factor in their safety.

4. Discussion

The results show that the levels of impact forces on the ground were generally consistent with the results obtained in other studies, especially by Fathallah and Cotnam (2000) and Patenaude et al. (2001). Variations in the results are discussed in relation to the methods of descent ("Facing the Truck" vs. "Facing the Street"), the design of the access system, and the perception of danger when stepping down from the vehicles. The different conditions in this study were themselves a combination of descending methods and the design of the accesses to the vehicles, the latter imposing the height of descent and the availability of handholds to control the descent. Why the perception of danger varies between fire stations is also discussed.

4.1. Impact forces and methods of descent

The results suggest that there was biomechanical stress on the lower limbs when stepping down from an emergency vehicle, but that this level of stress varied with the conditions of descent. For all the step-down conditions, the largest part of the impact force transmitted to the body came from the vertical descent movement. This explains why the anteroposterior and mediolateral components of the total force had little or possibly no effect on the sagittal and frontal forces, respectively.

For station "A", the largest impact forces on the ground were measured for "Facing the Street" step-down (condition "CREW-FS") as compared to descent at the same location but "Facing the Truck" (condition "CREW-FT"), which generated significantly less impact on the ground. For this latter condition, better control of the landing leg, as well as more frequent use of the hands to control descent, were observed in the video. The smallest vertical impact forces for station "A" were recorded for descent from the roof ladder (conditions "ROOF-LO" and "ROOF-HI"). Similar results were also observed with the fire fighters from station "B" during descents using a "Facing the Truck" technique ("PRUNR-FT" and "TLAD-FT"). Although this descent method generated the lowest values of biomechanical stress, there was the possibility of foot slippage in the frontal plane, particularly if the landing surface was uneven or inclined. In such a case, the exerted forces could cause eversion or inversion of the ankle to the limits of its joint mobility, thus causing a strain or a fracture.

At station "B", the two conditions in which the subjects stepped down "Facing the Street", "PCAB-FS" and "PRUNR-FS", also had the highest impact forces. In this last situation, the use of the handhold was non-existent and it was observed that the fire fighters controlled the start of the descent solely with the leg contralateral to that used for landing on the ground (see Fig. 5).

In both fire stations, the ‘‘Facing the Truck’’ method produced significantly less force on the ground. Based on observation in both fire stations and on a kinematic analysis performed on the descent of truck drivers (Patenaude et al., 2001), the most plausible explanation for these results would be that when the fire fighter's foot touched the ground, the largest part of the impact force transmitted to the body came from the vertical descent movement. When a fire fighter stepped down from an emergency vehicle ‘‘Facing the Street’’, the impact force could reach 6 times his body weight. The ‘‘Facing the Street’’ technique resulted in the fire fighter's body's centre of gravity being transferred in front of the supporting leg. This translation of the body's center of gravity could have resulted from its controlled bending of the knee (eccentric muscle work of the knee extensors) because very little bending of the hip was observed with this technique. In contrast to descending ‘‘Facing the Truck’’, this situation seems to have considerably limited the participation of the powerful extensor muscles of the hip (e.g., gluteal muscles). Also, the ‘‘Facing the Street’’ technique led to an observed imbalance frontward when the different masses of the body were no longer distributed in such a way as to maintain body stability above the supporting leg. As can be seen in the sagittal view of Fig. 1, the use of this technique resulted in shifting the body's centre of gravity away from the available supports (left hand and left foot). A medio-lateral imbalance can also be observed in the frontal view of Fig. 1. For the latter, the use of two ipsilateral supports most probably shifted the body's center of gravity toward the outside of the sustentation base. It is thus reasonable to think that it was mainly this loss of control of balance that increased the step-down speed, and as a result, increased the impulse forces to be dissipated on the ground at the time of impact.

On the other hand, by stepping down ‘‘Facing the Truck’’, the results show that the subjects were able to make greater use of the handholds to stabilize themselves. One plausible explanation for the lower levels of impact forces measured with this condition is that the fire fighters could control their speed of descent with the supporting leg by means of eccentric muscle contraction of the hip extensors and leg extensors. The use of the handholds reduced the speed of descent through the friction force between the hand and the handle. It is possible also that the use of handholds improved the body's stability with the supporting leg, particularly when the fire fighter used the hand contralateral to the supporting leg. As can be observed in the sagittal view in Fig. 2, the body's centre of gravity is kept near the supporting leg and, contrary to the ‘‘Facing the Street’’ technique, one can see in the frontal view in Fig. 2 that it is kept within the sustentation base. It is also reasonable to think that stability was also due to the fact that displacement of the body caused by flexion of the hip and knee of the supporting leg was compensated for by slight trunk flexion. This compensation would allow a better distribution of the body's masses above the supporting leg. This technique could also allow the landing leg to touch ground far from the step. Also, in all ‘‘Facing the Truck’’ conditions, the muscles responsible for plantar flexion (e.g., *triceps surea*) contributed to the absorption of energy because, from the tip of the toes on, the foot gradually came in full contact with the ground. This can be observed in Figs. 1 and 2. Overall, stepping down ‘‘Facing the Truck’’ facilitated the contribution of the upper limbs through the use of grab bars and handholds, and of the plantar flexors in the lower limbs to counteract the gravitational vector of descent.

4.2. *Influence of the truck design*

The magnitude of the force retransmitted to the body can also be related to the design of the ingress/egress on the vehicles. For station ‘‘A’’, the condition that resulted in the highest ground impact values is the descent from a crew cab ‘‘Facing the Street’’ (‘‘CREW-FS’’). The free-fall distance for that access point was 58 cm and the average of the impact forces was 3.6 BW. Two handholds were available, a grab bar on the inner left side of the door opening and a handle fixed on the inside of the door. The door opened to 90° but could not be blocked open in place. With the ‘‘Facing the Street’’ descent, it was difficult to use the grab bar located on the left side of the door when descending. Its current position, if it is used, rapidly caused an external rotation of the left shoulder when the fire fighter stepped off the last step of the crew cab. Also, the analysis of the video showed that some fire fighters had to step down carrying a tool in one of their hands, or held their SCBA mask to prevent it from swinging around. Descent ‘‘Facing the Truck’’ (‘‘CREW-FT’’) at the same location generated significantly less ground impact force, and a plausible explanation is proposed in the preceding section. However, descending ‘‘Facing the Truck’’ implied that the fire fighters had to turn around on the top step of the crew cab to be able to proceed backwards, a movement they had to do while wearing their air tank on their backs.

At fire station ‘‘B’’, the design of the driving cab limited the use of the steps (condition ‘‘PCAB-FS’’) and produced a force of 3.2 BW on landing. The pumper used at this station had a forward type driver's cab. This cab put the driver's station at 76 cm above ground and the door access just above the front wheels. The steps were therefore off-cener in relation to the center of the access door. This layout made the steps practically unusable during descent. The usual strategy observed in this group of fire fighters consisted of balancing themselves with the right hand on the upper edge of the fender of the cab and with the left hand on the window sill or the handle of the door, before free-falling to the ground (see Fig. 4). This is a technique in which the fire fighter found himself ''Facing the Street'' at the moment of contact with the ground. Landing was usually on both feet at the same time. The second highest (3.05 BW) average ground impact values recorded in station ''B'' were for the descent from the rear runner board of the pumper while ''Facing the Street'' (''PRUNR-FS''). At that location on the truck, the free-fall distance was 50.8 cm and a vertical hand rail was available on both sides of the runner board but was not used during the descent. However, stepping down from the same location ''Facing the Truck'' (''PRUNR-FT'') and using the handhold with the right hand produced significantly less ground impact force (1.6 BW). Stepping down from behind the tanker (''TLAD-FT'') produced values of the same magnitude. For the latter, the runner board was 85 cm from the ground, but a rung had been installed under the runner board that reduced the height of the descent to 45.75 cm. A hand hold 16 cm long had been welded vertically on the right-hand side at 175 cm from the ground, and was used by all the fire fighters when descending.

The access point that produced the smallest impact forces was the access ladder to the top of the elevating platform (''ROOF-HI'' and ''ROOF-LO''), located 167.6 cm from the ground. The rungs of this ladder were all 28 cm apart but there were no handholds. The presence of the retractable footstep (''ROOF-LO''), which reduced the descending height by 28 cm, had no significant effect on the impact forces. For these two conditions, it did not seem possible to step down ''Facing the Street''. The subjects used both their hands on the ladder rungs while descending ''Facing the Truck''.

4.3. Level of perceived danger

Regarding the perception of danger during descent, the condition of descent from the crew cab ''Facing the Truck'' was the condition considered as the least safe by the subjects in station ''A'', even though this descent condition led to the lowest level of biomechanical stress. This phenomenon was not investigated, but there can be several explanations for this paradox. The first one would be the better field of view offered to fire fighters who stepped down from the emergency vehicle ''Facing the Street''. This allowed them to check for the presence of other vehicles that could come on the street toward their trucks during an intervention. Also, as pointed out before, the video sequences taken of the descent showed some difficulty in making an about-face turn on the upper steps of the crew cab when the fire fighters were carrying air tanks on their backs. This lack of space could explain the negative perception of fire fighters from station ''A'' when descending from the crew cab. Third, even if no timing was done, it is reasonable to think that stepping out ''Facing the Street'' can be performed faster since there is no ''turning around'' to be done. Finally, as pointed out by Rhoades and Miller (1992), users (truck drivers, in their case) who stepped down from their driving cab ''Face out'' categorized their access system as a ''stair''. An access system where one steps down backwards with a ''three point of contact'' method is uncommon and it is thus possible that fire fighters also categorized the access to the crew cab as a ''stair'' rather than a ''ladder'', and used it as such.

In contrast, fire fighters from station ''B'' rated a moderate level of perceived danger only for stepping down from the rear runner board ''Facing the Street''. This may be due to the fact that they served a less dense and less populated community than those in station ''A'' and that heavy automobile traffic around emergency vehicles would be less of a problem for them. The concept of ''danger'' associated with the action of stepping down from a vehicle needs to be clarified in future studies. While the use of the psychophysical scale was intended to measure the perception of the risk of an injury or a fall while stepping down, it appears that it also measured other factors such as how the access system impedes movement, the risk of being struck by an oncoming car, or an organizational choice in order to get off the vehicle in the quickest manner.

4.4. Magnitude of the forces and biomechanical stress

The forces measured in this study were greater than those reported by Patenaude et al. (2001) in their study of descent from truck cabs, and they are equal to or less than some descent conditions carried out on other heavy trucks (Fathallah and Cotnam, 2000).

Table 4 summarizes the different ground impact values, expressed as multiples of body weight, obtained in the context of other studies in the fields of sports or transport. First, these values are seen to be high for conditions in which the distance to the ground during descent is high. In the study of Fathallah and Cotnam, for example, subjects were asked to jump with their feet together in a crouched position (''squat jump'') from a truck driver's cab 1.07 or 1.25 m from the ground, or from the van of a semi-trailer 1.14 m from the ground. Maximum values close to 7 times the subjects' BW were obtained. The highest values measured in the current study were in the order of 6 times the subjects' BW. However, it is important to realize that the fire fighting vehicles are the same size as those used in the study of Fathallah and Cotnam, and that similar conditions

Table 4
Comparison of ground impact values recorded when stepping down from different heights

Authors	Condition	Distance to ground (cm)	Ground impact (BW)	Ground impact (N)
Nigg et al. (1981)	Walking		1.5	
Nigg et al. (1981)	Running		5	
Patenaude et al. (2001)	Stepping down with 3 points of contact	53.5–41.5	1.36 ± 0.15	
Fathallah and Cotnam (2000)	Jumping down from a "COE" truck cab	125	7.1	5794 ± 2273
Fathallah and Cotnam (2000)	Jumping down from a "conventional" truck cab	107	7.2	5832 ± 1920
Fathallah and Cotnam (2000)	Same, but from the first step off the ground	43	1.8	1407 ± 421
Fathallah and Cotnam (2000)	Jumping down from a "step van" truck cab, no hand hold	43	3.5	2143 ± 688
Fathallah and Cotnam (2000)	Jumping down from a "step van" truck cab, with hand hold	43	1.9	1630 ± 457
Fathallah and Cotnam (2000)	Jumping down from a trailer' floor	114	6.4	4986 ± 1440
Fathallah and Cotnam (2000)	Jumping down from a trailer's step	36	2.1	1661 ± 498
Fathallah and Cotnam (2000)	Jumping down from a "cube van's" floor	71	5.5	4410 ± 1638
Fathallah and Cotnam (2000)	Jumping down from a "cube van's" step	49.3	1.4	1171 ± 471
Current study	Condition "CREW-FS" in fire station "A"	58	3.72	2952 ± 897
Current study	Condition "ROOF-LO" in fire station "A"	28	1.94	1571 ± 290
Current study	Condition "PCAB-FS" in fire station "B"	76.25	3.19	3238 ± 919
Current study	Condition "PRUNR-FT" in fire station "B"	58.8	1.6	1601 ± 219

could occur with fire fighters. This table also shows the biomechanical advantage of being able to control one's descent, particularly by opting to descend "Facing the Truck". One of the lowest values obtained (1.9 BW) in the study of Fathallah and Cotnam was in descent from a delivery truck by using the handholds. The study of Patenaude et al. obtained lower impact values at the ground for "Facing the Truck" descent conditions in which the "method of three support points" was used.

Based on the work with fresh cadavers by Yoganandan et al. (1997), ankle fractures occur with impact forces exceeding 10,200 N. Similar work (Klopp et al., 1997) mentions a 50% likelihood of fracture at the base of the tibia or fibula or of one of the foot bones for impact values of 9300 N. In all the descent conditions analyzed in this study, only one fire fighter had an impact force approaching 6000 N, namely a fire fighter who was stepping down from the cab "Facing the Street" so as to land on both feet at the moment of impact. The studies of Yaganandan et al. and of Klopp et al. were done using parts of the anatomy taken from fresh cadavers and were carried out in the context of the traumatology of road accidents. The results obtained in these types of studies cannot be assumed to be directly transposable to studies done with human volunteers, but some conditions present with fire fighters could approach the point of biomechanical fracture. Also, it is important to consider that the landing surface (ground) during descent from vehicles in an emergency situation is not always uniform. In this latter case, a force greater than 3 times the BW combined with ankle eversion or inversion would at least result in strain in the ligaments of this joint (Peterson and Renström, 1986).

4.5. Limits and reach of this study

Of course, these results mostly apply to a sample of 18 fire fighters and to three of the 2129 fire trucks registered in the province of Quebec (MSPQ, 1995). Even if these vehicles were representative of the fleet of fire trucks usually found in fire stations, the combination of chassis, installed equipment, and local adaptations makes it difficult to provide recommendations for each case. The study lacks anthropometric data and the sample did not include any female fire fighters. It also lacks randomization, a bias necessitated by the constraint of having to work with laboratory methods in the field. The values were recorded and the observations were made in the absence of any urgency, and the impact forces or the use of hand support might differ during an emergency response. The quality of the ground in an emergency response zone can also be very different from the clean surface of a force platform. However, the collaboration of the steering committee in identifying the descent conditions, and the participation of full-time and trained volunteer fire fighters, with their own equipment for the measurements, speaks to the realism of the results.

This study touches on other issues related to stepping in and out of heavy or off-road vehicles that are not covered here. While the emergency vehicles' driving cabs can meet dimensional standards, this might not be the case for other points of access or for the crew cabs, even if fire fighting standards advocate the use of the "three points of contact" method on all vehicles (ULC, 1996; NFPA, 1999). The recommendations proposed by vehicular standards such as ISO 2867 (1994) or SAE (1993) do not necessarily correspond to the needs of fire fighters, such as wearing protective equipment, carrying tools, and time constraints when stepping in and out. Based on our sample of vehicles, the current design of some of the accesses did not allow fire fighters to benefit from the positive elements of each of the descent methods. Reflection is thus needed to better address their specific needs concerning ingress/egress, and in the absence of fire truck manufacturers locally, it becomes difficult to involve design teams to work on that issue. Further research would also be welcome on the perception of danger when using an access system, and on ankle stabilization through the use of proper footwear.

4.6. Recommendations

The research team's recommendations to the steering committee are that joint occupational health and safety committees in local fire departments should act to make "three points of contact" access available to all parts of the emergency vehicles, not just for the driving or crew cab. This includes access to the mechanical ladder or platform, as well as to the hose storage and deck gun compartments atop pumpers, from the rear or from the sides of the vehicle. However, the recommendations accept stepping out "Facing the Street" as long as two opposite diagonal points of contact are available. A possible solution, as applied to the crew cab where the measures were taken in station "A", consists of the installation a vertical grab bar inside the door, on the side opposite the hinges: a better control of the descent speed could thus be achieved by friction of the hand on the grab bar, or by using the eccentric force of the right shoulder extensors to reduce or to cancel the free-fall descent from the last step. This handholds could be stabilized by locking the door in the open position. Also, increasing the windowed area of the door would improve the collection of visual information by allowing the users better monitoring of the presence of traffic when stepping out.

In order to help the local OHS committees to evaluate the accesses to their vehicles, it was recommended that an informative document and a checklist be designed to help fire departments audit their vehicles. On a more technical basis, it recommended that the dimensions of hand rails be compliant with the values stated in ULC S-515; especially, in relation to wearing thick gloves, and that all steps, footholds and rungs have non-slip surfaces, and that they be used with the safety footwear usually worn by fire fighters. A full report, with the recommendations, is available (Giguère and Marchand, 2002) and technical advisers for the joint OHS association for municipal workers (APSAM) can help out fire departments locally. Finally, efforts should be made by standards organizations to include a comprehensive definition of a "three points of contact" method of access whenever its use is proposed in the text of a standard; design guidelines, and ways to measure its effectiveness and user friendliness, should also accompany it.

5. Conclusion

This study was set up to investigate the role of impact forces on the lower limbs of fire fighters stepping down from fire trucks. The values that were measured are consistent with those found in other studies, and the causes of the variation in the data are of interest in accident reduction. Basically, stepping down "Facing the Street" does generate higher ground impact figures, while using the "Facing the Truck" method at the same location did produce significantly lower values. Some vehicle designs, through the placement of handholds and rails, proved successful in providing a better control of the movements and in reducing the speed of descent. Designs that encourage stepping down "Facing the Truck" should be made available to the fire fighters, who should have their hands free to be able to use them. Fire fighters must also be informed, through continuing safety education, that stepping out "Facing the Truck" with a "three points of contact" method is less detrimental for them. Designers of such vehicles are encouraged to take into account the special safety needs of fire fighters as users of emergency vehicles.

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