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Physical parameters of free fall in a child

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Abbreviations

a = deceleration
d = depth of imprint left on ground by the body
Δr = body deformation
E = energy
F = force
g = acceleration due to gravity
h = height
Θ = momentum
m = mass
P = power
s = deceleration distance
t = time
v = velocity

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Introduction

We report the case of a baby who survived a particularly long fall, and discuss the physical parameters involved.

Case report

A 21-month-old boy was brought to a local Accident and Emergency department by ambulance. The child was discovered by a neighbour lying on the ground on his left hand side at the bottom of a high-rise building, screaming and having vomited.

On arrival, he was conscious (modified children's Glasgow Coma Scale score = 13), tachycardic (160/min) and tachypnoeic (60/min), with a blood pressure of 100/60 mmHg and oxygen saturation of 97 per cent. There were bruises on the right side of his face, flank and leg. Routine injury management and stabilization was instigated immediately. The presence of a right sided pneumothorax was confirmed with a chest X-ray. Pelvic X-ray revealed a fracture of the left superior pubic ramus. The patient was transferred to the paediatric ITU of our hospital. An emergency head CT scan was essentially normal. An abdominal ultrasound scan revealed free intraperitoneal fluid, and a bulky spleen. An abdominal CT scan with dynamic intravenous contrast enhancement subsequently revealed a rupture and a small contusion of the posterior segment of the right lobe of the liver, a Y-shaped rupture and posterior contusion of the spleen, along with a haemoperitoneum and a left pleural effusion and atelectasis. The liver enzymes were elevated. Within the first 24 h of admission, the police expressed strong interest in this case. They presented physical evidence, which indicated that it would be virtually impossible for the baby to have climbed and fallen by himself. His mother did not visit regularly, and most communications were through the maternal grandparents. The social work department was duly involved and a place of safety order obtained. The patient was treated non-operatively with blood transfusion and he gradually recovered. Complete healing of the visceral ruptures was confirmed by serial ultrasound scans over a period of 8 months. The child was discharged to the care of foster parents.

Mathematical evaluation of the free-falling child[1–3]

To calculate the speed of impact following a fall from a height of 35 m, air resistance can be ignored[1–3]. Solving the energy conservation equations[3] for v:

$$v_{\text{impact}} = \sqrt{2gh}$$

Upon impact (*Figure 1*), the body will abruptly decelerate to standstill in a finite time, t, and over a very short distance, s, equal to the linear deformation, Δr, of the body plus the depth it has impressed into the ground, d. This deceleration will be the result of a massive force which relates to the body's momentum, Θ, at impact as follows.

The deceleration time and the power (P) of such an energy dissipation can be determined by solving

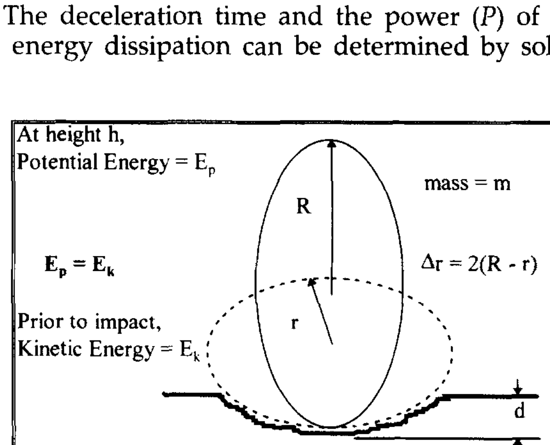

Figure 1. Theoretical analysis of impact of body after free fall from a height h. The body will suffer deformation r and will leave an imprint of depth d on soft ground.

Table I. Decelerating force and calculated power dissipation if impact occurred on concrete or wet grass

Impact surface	*Deceleration (× g)*	*Decelerating force (kN)*	*Power dissipation (kW)*
Concrete	346	40.5	535
Wet grass	232	27.3	358

the velocity and deceleration equations for t and substituting the symbols appropriately.

$$F_{decel} = \frac{d\Theta_{impact}}{dt}$$

Calculations

The following represent the measured parameters:

$m = 12$ kg, $g = 9.81$ ms^{-2}, $\Delta d = 10$ cm (assumed, see *Figure 1*), $d = 5$ cm (measured by police).

Substituting $s_{grass} = 15$ cm, $t_{grass} = 11.5$ ms for a fall on wet grass, or $s_{concrete} = 10$ cm, $t_{concrete} = 7.7$ ms if the baby fell on concrete, we get $v_{impact} = 26.2$ ms^{-1} (equivalent to approximately 59 mph (94.4 km/h)) and energy at impact = 4120 joules.

Other derived parameters appear in *Table I*.

Discussion

There has been considerable interest in the epidemiology of falls from a height including anecdotal or historical accounts[4]. Reports of surviving extreme impacts are rare but famous; the case of Flight-Sergeant N.S. Alkemade who fell without a parachute from a blazing Lancaster bomber flying at 18000 feet (5540 m) and survived is referred to in Royal Air Force archives. A fall from a height of greater than six storeys is almost universally fatal in adults[5]; a fall from the height of a nine-storey building (35 m), therefore, is likely to be fatal, but was not so for this child.

Infants tend to suffer significant injuries only if falling off a height of greater than 3–14 m, with one fatality after a fall of 23 m[6]. Because of the greater elasticity in the body of a child, the attitude of the body upon impact, and not the free fall height may be the most important determinant of mortality[7].

Impact along the coronal axis of the body would allow more linear deformation to occur during impact (*Figure 1*). This child was found lying on his left side. This, along with the fact that the left pubic ramus was fractured and that the solid visceral injuries were more severe on the left side, is consistent with the impact being along that axis. The deformation is assumed to be approximately 33 per cent of the long axis of the thorax. In a pilot study in minipigs (unpublished observation), rib fractures occurred after the thorax was compressed to 50 per cent of its initial diameter.

The survival of this baby could in part be attributed to the following factors: part of the energy of impact was absorbed by the elasticity of the immature bones[8] allowing for reversible body deformation (the 10 cm of deformation assumed, represents approximately one-third of the lateral diameter of the trunk); the baby's impact point on the grass was only about 20 cm from the concrete pathway; the 'cushion' effect offered by the soft wet grass may have absorbed up to 33 per cent of the energy of impact (*Table I*).

The maximum deceleration which the body can sustain is inversely proportional to the duration of exposure, and volunteers have survived deceleration of up to 40 g for 40 ms[9]. The deceleration which this baby suffered is calculated at 232 g, being applied for a brief period (<11.5 ms). Had the impact been on concrete, the magnitude of these parameters would have been even higher, almost certainly fatal (*Table I*). This simplified analysis will give an indication of the magnitude of the decelerating force acting on the body, but cannot predict the patterns of injury, as this depends on the differential movement of viscera of different mass. The deceleration is also assumed to be constant to allow straightforward calculation of the deceleration time. This may not be the case as deceleration will decrease as the energy is being dissipated. The mechanics of the soil are also important: the depth of the imprint might have been deeper than measured during the initial milliseconds of the impact. This may have allowed even more energy to be absorbed by some degree of elastic soil deformation. If this was the case, then the energy proportion absorbed by the soil would be even greater than we calculated and this would have contributed further to the child's survival.

The short distance between the wall and the point of impact meant that the baby's 'exit velocity' from the balcony was almost zero, consistent with being dropped and not being thrown. On presenting the foregoing evidence to the authorities and the relatives, the mother admitted that she had dropped the baby from the window.

Violence against children by their parents or carers is not a new entity and it has been recently reviewed[10]. The possibility of non-accidental injury or, indeed, criminal injury will be missed unless suspected, duly investigated and reported by the clinician.

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