Motor safety of a man during a fall

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Abstract

The purpose of the present work is to review the key research methods as well as the existing knowledge of biomechanics on human motor safety when during a fall. The second goal of the paper is a biomechanical analysis of falls performed in a rotational motion on the ground, by reference of the movement of a man to a car wheel rolling. The analysis leads to the conclusion that during such a fall the energy of the body deformation per volume unit of the body parts touching the ground can be reduced by minimizing the time of the body contact with the surface and by increasing the area of body parts in contact with the surface. Decreasing the time of the body contact with the surface can be achieved by increasing, to some extent, the velocity of the body rolling. A factor increasing the contact surfaces can be extending a radius of the circle on which the fall continues. This can also decrease the rolling resistance strength, which is responsible for non-elastic body deformation. The knowledge of biomechanics contained in this paper proves the correctness of the statement, that "suffering an injury" does not necessarily mean to be an unavoidable consequence of a fall. Body injuries can be weakened through a proper technique of falling, applied in particular physical conditions generating a fall. In the majority of cases the contemporary educational systems do not see properly the necessity of teaching safe falls. Taking adequate preference actions in this area would reduce significantly fatal accidents and serious injuries to a body caused by falls, especially of elderly people and professionals who are frequently exposed to falls.

Key words: biomechanics of a fall · body injuries · falling technique · martial arts · rotational motion

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koho-ukemi – rear fall

yoko-ukemi – fall to the side

Introduction

A human being when moving, as a result of unexpected forces acting on him, can lose his balance and hit the ground on which he is moving or collide with an object such as a wall, table, etc. Such accidents can cause mechanical injuries of the body which can be harmful. During a mechanical movement a person's body reaches a certain velocity. A sudden change of the velocity causes an acceleration which is due to occurrence of forces related to the principles of mechanics. These forces affect particular body segments respectively. Owing to the fact, that human body is not a homogenous solid and contains a lot of water, a mechanic injury can cause its deformations both internal as well as external. Forces of inertia can cause injuries to internal organs.

A degree of health loss depends on the vulnerability of those organs to the effect of the forces. One of the most dangerous mechanical injury of a human body is head injury affecting especially man's nervous system. An example here can be a knockout during a boxing match, that can lead to a temporary loss of consciousness, and sometimes to a certain health damage.

Motor safety has been defined, as a consciousness of a person going to perform a physical task or a consciousness of a subject, who has the right to encourage that person or even force him/her to perform a certain physical task, which he is able to perform without a risk of losing life, injury or any other health side effects [1].

A man can perform particular physical tasks consciously taking a risk of a mechanical injury, for example, in sports, when working for police or military services, etc. However, this mechanical injury can often be brought about by mechanical circumstances, which surprised the subject. For the defined forces affecting a man causing a particular acceleration, his defensive reaction can be insufficient to avoid mechanical injuries of his body, for example, in a car accident, during a fall from a certain height. However, under certain circumstances, for example, with smaller forces acting on a man, it is possible to avoid or reduce a degree of man's body mechanical injuries. As numerous reports state, falls often lead to health loss.

According to WHO, a fall is an incident as a result of which a man unintentionally found himself on the ground, floor, another surface on a lower level [2]. Some define a fall as an incident caused by a sudden, unintentional change of body position as a result of loss of balance leading to a man finding himself on the ground, floor or another lower located surface. This definition provided by Żak [3] is based on the research work of Hauer et al. [4] as well as Feder et al. [5].

A broad group of researchers supporting the above fall definition dealt with a fall in view of its medical aspects by analysing an effect that various diseases might have on falls. A possibility of a defensive reaction of a falling person, that could reduce the effects of body injuries as a result of contacting the ground, can be restricted by development of a particular disease. It is especially impossible in case of losing consciousness causing a fall. At the same time, some other researchers study human behaviour affected by external forces causing his loss of balance, that could lead to involuntary change of the body position onto a lower level [6-10]. Such research is carried out in order to reduce body injuries as a result of a fall suffered by workers in their place of work as a result of occurrence of external forces causing a fall [11].

The author of this paper interprets the definition of a fall of a man approached according to the general, official definition by WHO. However, in his attempts he confines himself to the falls in which a person is able to perform a certain defensive response during a fall. Such a response is obviously restricted in case of certain disease symptoms and impossible in case of a loss of consciousness. A defensive response can also be unworkable in the situation when there are big forces affecting a man, which make it impossible for him to react in any way. As all changes in a human body velocity are a result of forces acting on the man and every fall is a result of a change of the velocity, when classifying reasons of falls it is right to divide them depending on the acting forces. The author of the present paper suggests to stick to the biomechanical division of forces acting on the human locomotor system [12]. Thus, external forces are the forces affecting human locomotor system from the outside, such as gravity, wind, partner/ opponent, friction reactions of the ground. Internal forces are the forces generated by the active locomotor system of a man and the resistance they create. The active system comprises skeletal muscles. Kalina indicates three types of reasons for falls [13, 14].

The first one is related to a lack of balance of external forces acting on a man, who has no influence on them. Such external forces acing on a man can comprise, for example, hitting with a certain object, such as colliding with another competitor during a match or with a cyclist. Examples of such forces can be forces of inertia acting on people on a bus, streetcar or another vehicle, which is changing its velocity abruptly.

The second type of reasons for falls results from external forces generated by a man due to his motor activity performed on a relatively stable surface. Incorrect performance of a certain motor task by a dancer, gymnast can end up with a fall. The third type of reasons for falls involves occurrence of both external and internal forces during a fall. Fall reasons of that kind belong to the broadest category and are frequently met. As an example here can serve a fall during a cross country run as a result of slipping on the ground on which a friction ratio changed suddenly. Another example can be doing trampoline jumps, when a gymnast has not performed a certain figure and fell off the trampoline onto the ground.

The author of the present paper thinks, that factors increasing forces that might lead to a fall is a sudden change of a direction in which a person is moving. Transfer from a rectilinear movement into a curvilinear movement increases the effect of external forces that are responsible for a fall. At the moment of changing a movement direction a force of inertia occurs. The person being in such a movement is affected by a centrifugal force, which with a small friction force of a surface can lead to slipping. Apart from that, at the moment the curvilinear movement of a man's body segments and especially during the occurrence of a rotational motion the forces of inertia affect the man's internal organs. The accompanying angular accelerations have an effect on the man›s sense of balance requiring certain reactions from him. Failure to react in time to sudden changes in a rotational motion, for example in sport, can be a cause of a fall.

The purpose of the present work is to review the key research methods as well as the existing knowledge of biomechanics on human motor safety when during a fall. The second goal of the paper is a biomechanical analysis of falls performed in a rotational motion on the ground, by reference of the movement of a man to a car wheel rolling.

Fall research methods

The problem of injuries suffered by men as a result of falls is broadly approached. However, most frequently researchers deal with fall prevention by promoting health care, better care of elderly people, decreasing external factors of environment that can cause falls, such as proper surface on which we walk, better footwear, lighting etc. [11, 15-17]. Nevertheless, there are some authors who claim that through an adequate training, a man can improve his locomotor habits leading to a smaller number of body injuries as a result of a fall [1, 13, 14].

Many researchers study human behaviour at the moment the balance is disturbed by certain driving forces [7, 9]. It is obvious, that improving man's resistance to balance disturbances can prevent a fall. There has been a non-apparatus rotational test developed [14, 18], which diagnoses maintenance of balance by a man in rotational motion. The test shows, that better results are achieved by people, who, in the sports disciplines they practice, are frequently subjected to external forces causing loss of balance. For testing balance of people in danger of a fall certain balance platforms are used, that is devices, that measure a throw of the centre of gravity on the surface of feet support [19-23]. The obtained results of maintaining balance in the vertical posture show that this ability is weaker in elderly people and it deteriorates along with age [11, 20, 23]. For testing reactions of moving people to forces that might lead to a fall various types of treadmills that can generate acceleration acting on a man and causing loss of balance are used [7]. The same principles of operation are applied in various platforms and tools, blocking, for example a person's foot, when moving backwards [8, 9, 11]. The common feature of all these methods is that they analyse a person's response to sudden forces leading to losing his balance, however, the subject's fall, that means his contact with the ground, is not allowed. For this purpose a special harness is used, which makes it possible for a person to become suspended when the balance is lost. This ensures the person's security during the experiment. It is necessary, because the surface the persons moves on is close to the conditions the person is moving under in his everyday life. Thus, the surface is not provided with certain mats, that could reduce the impact and body injuries during a fall. From the point of view of motor safety of a man it is crucial to avoid falls, therefore, all research works on man's response to disturbances of his balance are important, since what matters is balance loss prevention.

Man's contact with the ground can additionally be dangerous, due to certain sharp objects existing there, such as pieces of glass, stones, etc. [24]. However, in his lifetime a man can be challenged by forces generating such an acceleration, that avoiding a fall is practically impossible. The forces may be so enormous that a man may have no chances to react in any way. If, however, the forces acting on the man are within such limits that the reaction by a falling man is possible, it is important what physical steps the falling person will take when falling. According to Kalina and co-authors, it is not true, that unavoidable consequence of losing a balance and falling to the ground is "having an injury" [24]. In the situation of a sudden loss of balance, a trained person will promptly control various parts of his body, adequately in line with the direction of falling or the acting forces. The common assumption of a physical activity during a fall is the ability to control various body parts so that, when there are no external factors facilitating an injury, most frequently a fall will be correctly absorbed by the man's locomotor system. Numerous book references show that, owing to a certain technique, a man is able to reduce injuries of his body resulting from contacting the ground in a fall [24-27]. Gąsienica-Walczak et al. defined the falling technique as hitting the ground by a man safely in one of the four basic directions: backwards, forward, to the side (right, left) [25]. The author of the present paper understands the falling technique as making a certain motor task depending on the fall direction, so that the body can safely contact the ground during a fall.

During a fall the most vulnerable body parts at the moment of hitting the ground are head, arms and pelvic girdle. Kalina elaborated a test of susceptibility to injuries during falls (STBIDF) [24, 28, 29]. The test is based on a simulation of the simplest situation in which a person loses his balance and hits the ground during a fall backwards. The test is performed by eliciting a fall by the subject's own forces. By evaluating the contact of the head, arms and pelvic girdle, the test diagnoses the risk of injuring particular body parts when falling backwards.

Some books references state, that a man when exercising on an apparatus enforcing a loss of balance can practice his skill to maintain the balance that would allow him to avoid falls in his daily life [9, 10]. However, there has been no references to an apparatus on which a man could improve the technique of a fall caused by big forces preventing him from keeping balance. When doing various types of gymnastic exercises, in order to reduce unfavourable effects of falls, certain mats are used. A proper ground for falling can reduce an energy deforming a body during a fall and reduce the risk of a body injury. Preliminary results that the author of the present paper has obtained suggest, that a rotating training simulator could be used as an apparatus method of evaluating susceptibility to body injuries during falls [30, 31]. Such an apparatus ensures evaluation of a falling technique as well as its improvement by exercising on it (unpublished materials). A fall elicited by means of this device is performed on a properly thick layer of mats. The fall is made as a result of abruptly stopping the rotating platform with an exercising on it subject, whose velocity is accelerated to reach the defined angular velocity. Application of the apparatus of that kind would be of special importance to people, who in their work may encounter forces responsible for a fall. Such people may, for example, include firemen, soldiers, policemen, stuntmen or athletes of various sports disciplines. A right falling technique is important also for an ordinary man, because the training simulator can simulate a fall, for example, when the man is standing on the bus, which stops suddenly. Although, such a situation happens quite rarely, its effects in case of, for example hitting the head against an object, may lead to a serious health loss.

Apart from analysing the presented above methods, improving the ability to keep balance in order to avoid a fall and improving the falling technique, it is also important to remember about developing the ability to avoid forces responsible for a fall. We often read or hear about recommendations to, for example, care properly for the floor in the place of work or in houses, especially where the diseased people are, in order to prevent people from falling. However, some falls are due to collisions [25]. A person may be hit by a certain object, for example, by a walking man, a cyclist or an object thrown. The ability to avoid such incidents is related to a quick change of the body position at the moment the person is threatened with the collision. Such skills are developed by people practicing martial arts, where the principle yield to win rules. By avoiding the force of the opponent it is possible to perform a counter-technique. The speed of avoiding collisions is developed especially in such arts as kendo, where on how quickly you move and react victory depends. Correct habits of avoiding collisions are frequently improved through game activities applied in martial arts, for example in the game "matador" often referred to in research reports [25, 27].

Biomechanical determinants of motor safety of a man during a fall

The first attempts of a biomechanical analysis of a man's fall were presented by Jaskólski and Nowacki [32]. The mechanical energy that a moving person has consists of kinetic energy $E_k = mV^2/2$ and potential energy $E_p = mgh$. If the man's centre of gravity is lowered due to a fall, reduction of the potential energy due to a fall leads to an increase of kinetic energy.

$$mgh_2 - mgh_1 = mV^2/2 \quad (1)$$

If, before the fall, the person has the defined velocity of V_0, then the formula for the kinetic energy at the moment of hitting the ground can take the form of

$$mV^2/2 = mV_0^2/2 + mgh_2 - mgh_1 \quad (2)$$

where:

m – body weight

h – the height of the man's centre of gravity (h_2 – before the fall, h_1 – after the fall)

g – gravitational accelerations

Jaskólski and Nowacki analyzed the energy of a human body deformation during a fall assuming the body surface as homogenous and resilient. They assumed that all the energy of a falling person converts into deformation energy. They established, that the deformation was the sum of shape and volume deformations. From mechanical point of view, transformation of the formula onto this energy is close to considering the elastic strain energy of a prismatic bar stretched with an axial force [33]. The authors accepted the same analysis method both for the bar tension and compression. During a fall of a man there occur mainly compression forces causing strains on the man's body. They obtained the formula for kinetic energy of deformation per a volume unit

$$e=\frac{m^2 \cdot dV^2}{2E\,t^2 S^2} \tag{3}$$

where

dV – a difference in velocity between and after the fall, which is practically equal to the component velocity just before the incident, because, as a result of the collision, the final velocity of the body equals zero

E – Young's modulus

S – surface affected by the force

t – time of deceleration during the collision

m – man's body weight

If, in the formula we mark with k the values a man does not have any influence on during a fall

$$k=\frac{m^2 \cdot dV^2}{2E} \tag{4}$$

the formula will take the following form

$$e=\frac{k}{t^2 S^2} \tag{5}$$

The formula obtained (5) justifies the statement that the deformation energy per the man's body volume unit can be reduced during a fall by increasing the area contacting the ground and by extending the time of this contact. The same conclusions, as far as falling techniques are concerned, were reached by Reguli and co-authors [34] stressing the necessity of distributing forces during a fall onto possibly the biggest area and suppressing the fall in possibly the longest time. Formula (3) shows, that an increase of the velocity, with which particular body parts during a fall hit the ground, causes a sudden increase of the body deformation energy per volume unit, because dV in the formula is squared. When formulating the formulas it was assumed that during a fall the body stops completely. Therefore, the chances of avoiding a fall are very little in case of high velocity before the fall. This is similar as in the case of a car colliding with a wall, which cannot be moved.

Jaskólski et al indicate the role of muscles, which absorb the body shocks [27, 32]. The common feature of soft tissues is their non-linear behaviour within the range of moderately big and big deformations [35-37]. Their description can be made in terms of hyper-elasticity. In testing properties of soft tissues there are references to reports comparing elastic properties of soft tissues to rubber-like materials [35, 38]. However, there is no reference to differences in deformations of compressed muscles activated differently. However, the tests made were not based on live tissues.

The author of the present paper claims, that deformations of soft tissues, especially muscles, during falls can roughly be compared with deformations of rubber-like materials. In order to make the interpretation of this phenomenon easier, when explaining human body deformations, we can make a reference to deformations of a car tyre. An important structural component of a tyre is rubber defined as a hyper elastic material [39, 40].

The biomechanical analysis of a fall presented by Jaskólski and Nowacki does not comprise an analysis of energy of human body deformations, when the body is performing a rotational motion on the ground. In sports disciplines, where athletes frequently fall it is very common. An athlete, when falling, arranges his body in such a way so that the line of the body contact with the ground follows a circle. After accepting a certain technique of falling forward or backward, after performing a single roll over the line of the chest, the subject comes back to the standing posture.

The considerations here can be made easier by accepting a model in which during a fall a human body behaves similarly to a rolling car wheel. This comparison is obviously a certain simplification, because during a fall human body segments do not take a shape of a filled wheel. A human body is not homogenous, during a rotational movement in it there occur forces of inertia. A car wheel rolls well, when the tyre is properly filled up so that there is no direct contact of the surface with the rim. Following a similar interpretation, it would be best if a human body during a fall could amortize the contact with muscles and not with bones. Our muscles, according to the above approach, play a similar role to a car tyre and the bones can be here compared to rims. Percentage deformation for ultimate strength is bigger for bones than for muscles [41, 42]. At the same time, the ultimate strength itself is bigger for bones than for muscles. This shows that by rolling over using muscles more and with smaller strains there are bigger deformations than for bones. This makes it possible for muscles to adapt its shape to the shape of the surface to which they are pressed. Rolling of a man over using mostly muscles can be compared to a tyre wheel and rolling directly with bones to a tyre-less wheel with a metal rim.

According to the author of the present paper, in case of determining strain energy during rolling of a man's body as compared with a car wheel, the formula 5 will not apply in full. It is obvious, that strain energy per a volume unit will be smaller, if the body surface contacting the ground is big. Therefore, it is better to roll over with the biggest area of muscles involved. It is obvious that heavier cars have wheels with both bigger diameter and wider, this ensures a greater contact of the tyre surface with the ground. It also happens, that on a single axis there are more wheels than two in order to enlarge the contact surface. Book references state [43] that, within certain speed limits, when this speed is increasing without sudden accelerations, deformation of the car wheel tyre decreases. It seems obvious, even when a person is watching first an immobile car and then when it is starting to move. Tyre deformation is reduced when contacting the ground along with a slow speed increase. This means, that if we shorten the time of a contact of a tyre with the ground, strain energy per surface area decreases. The formula 5 will not correctly represent this phenomenon for time variable. This is because it was formulated for a body hitting a ground in a progressive movement, for example, similarly to a car hitting an obstacle. It is obvious for this case, that the longer the time of the car speed change, the smaller the force of inertia affecting the passengers.

The above considerations show, that when a human body is rolling, some increase in the rolling velocity without big accelerations can reduce decrease of the strain the human body is affected by at the moment it contacts the ground. This is a result of the fact, that reducing the time of the body contact with the ground can decrease the energy of the body deformation during a fall, provided the body is rolling in the same way as a car wheel. An experimental analysis of such cases can serve in order to justify the above theory. An interesting form of performing falls forward is presented by the National Geographic by Ryan Doyle and Daniel Illabace exercising on a show jumping course [44]. The film shows a dummy falling from a certain height, and then a fall of a person practicing on the course. It was found, that when during a fall a subject assumed a circular technique of the body motion, that is the considered above technique of the car wheel, the force with which the body hit the ground was much smaller than in case of the dummy under the same circumstances. Despite the fact that, at the moment of the fall, the subject possessed a bigger velocity than the dummy hitting the ground.

It happens that a fall forward is not performed by rolling over, but, similarly as with volleyball players, in a form of the so called volleyball fall, by throwing the body forward when catching the ball in the vertical position is not possible. It is often accompanied by slipping on the surface. Then, when the body contacts the ground, there occurs sliding friction and the formula expressing conversion of potential energy during the fall takes the following form:

$$mgh_2 - mgh_1 = mV^2/2 + sT_s \quad (6)$$

$$mg(h_2 - h_1) = mV^2/2 + sf_sN \quad (7)$$

s – movement course
T_s – sliding friction
f_s – sliding friction coefficient
N – contact force

If, the fall is performed following a rotational motion similarly to a rolling wheel (Figure 1), the conversion of potential energy takes the form:

$$mgh_2 - mgh_1 = mV^2/2 + Iw^2/2 + sT_t$$

Figure 1. Fall backwards made by rolling over

With some degree of approximation it can be acknowledged that:

$T_t = f_t N/R$ (8)

$mg(h_2 - h_1) = mV^2/2 + Iw^2/2 + s f_t N/R$ (9)

f_t – sliding friction coefficient
N – contact force
R – radius of the circle on which the subject is moving
T_t – sliding friction
I – moment of inertia
w – angular velocity

After rolling away the person performing a fall can retake the standing posture by converting kinetic energy that has not been lost for the potential one. Following the volleyball-like method of a fall entails doing more work related to friction than when rolling on a circle (formulas 7 and 9). This results from the fact, that sliding friction forces are greater than rolling friction forces [45]. Reguli and co-authors stress, in general principles concerning falling techniques [34], that by rolling when falling and not slipping, the affected people can avoid bruises and abrasions.

Formula 8 also shows that performing a fall following a greater radius R will reduce the value of the rolling friction force. Friction in a body rolling motion is not caused by the same circumstances as in the sliding friction when irregularities of friction surfaces catch hold of one another; its reasons are a result of various phenomena that occur during impact, compression or separating a rolling body from the ground. A rolling body contacts the ground not in a single point, but over a certain area. The main component of energy loss of a tyre wheel are the losses related to tyre deformation [43].

When a wheel is rolling some power is used for deformation of the tire. When the tyre is decompressing it regains some of this power, however it is smaller than the power put into. The difference in the energy is transferred onto internal friction of the tyre material. This loss is called hysteresis. Rolling friction is associated with plastic strain of the surface on which a body is rolling and the surface of the rolling body itself. In reality, there are no ideally elastic strains. There are methods of determining a friction coefficient for a rolling body [45], however, there are no references to a human body in this matter. Furthermore, the attempts to determine such a coefficient would be difficult due to the fact, that the thing that the body will assume a shape of a circle when contacting the ground would not be enough for an accurate determination of this coefficient. This is because that elastic properties of tissues that cover particular segments of a human body are different on, for example, head and in the area of buttocks. Furthermore, elastic features of muscles can vary depending on their activation. According to the author, a change in the muscle activation status can, to some extent, be compared to changes in the car tyre pressure.

The above reasoning leads to a conclusion that some energy spent on work related to rolling friction of a human body can cause certain body injuries due to non-elastic strain. Also, such strains can increase due to having not assumed exactly spherical surface of the contact with the ground. In order to reduce the strains, it is reasonable to aim at reducing the value of the rolling friction when falling by rolling over. This can definitely be lowered by increasing the radius of the circle (formula 8) on which the falling person is moving, as well as by wearing proper clothes. To some degree of approximation we can state, that proper clothes can, during a fall, contribute to reducing the friction force in the same way as tire tread.

If, before a fall a subject has a defined velocity V_0 then, the formula 9 should be supplemented with the initial kinetic energy

$mV_0^2/2 + mg(h_2 - h_1) = mV^2/2 + Iw^2/2 + s f_t N/R$ (10)

Similar procedure should be applied for formula 7.

Formulas 9 and 10 do not take into account elastic energy when a body is rolling, because it does not generate any losses of the body kinetic energy. This is a result of the fact, that the strained body part, when contacting the ground, after removing the contact force due to the continuing rolling, retakes its previous position. Mechanical energy losses during a fall are a result of the work related to friction. Taking the elastic energy into account was necessary in formula 3 by Jaskólski and Nowacki, because their analysis provided for the total conversion of kinetic energy into elastic energy.

The analysis of the conversion of the energy types occurring during a fall performed in a circular movement leads to a conclusion, that the energy of a human body strain per single volume unit can be reduced by increasing the area of the surface in contact with the ground and by decreasing the time of the body contact with the ground. A factor increasing contact surfaces with the ground is extending a radius of the circle on which the movement continues. Increasing the speed of rolling, of course to some extent, can reduce the strain energy by shortening the time of the impact. This condition is met during a fall when the falling technique ensures that the body performs a circular movement. After reaching a certain linear velocity, body parts contacting the ground during rolling over, should not obtain high linear accelerations, both positive as well as negative. Big accelerations could lead to an increase of forces deforming muscles during a fall. An example here can be a car tyre, whose deformation is visible both during acceleration as well as deceleration. If body parts contacting the ground are not arranged in a circle, then they will be affected by collisions, thus more exposed to a greater tension.

There are various methods of falling, however, the purpose of the present article is not to evaluate them, but to present biomechanical determinants that reduce the expected body injuries. With a high speed of a person falling forward, as volleyball players do, and with a surface with a high friction coefficient, a fall is difficult to perform and unsafe. In combat sports when falling backwards, competitors do some work by properly hitting mats with their hand at a certain angle. The impact can reduce kinetic energy with which particular segments of the body are hitting the ground [46]. However, a frequent response by people not practicing falls, that is supporting their body with arms suddenly thrown backwards, is incorrect [24]. This can cause fractures or serious injuries of joints in upper arms and shoulders. In case of big forces and velocities occurring during a fall, it is important to assume the body contact with the ground following a circle. It is clear, that tyres rub off the least and obtain smallest deformations, if car wheels when braking are not blocked, but continue to roll. Therefore, providing the human body during a fall with a possibility of rolling can reduce body strains. It is important, that the contact line with the ground is properly long and the first contact is not an impact at the same time (Figure 1).

It is also better to continue during a fall a movement following a circle with a greater radius R, which is explained by the formula 8. When certain body parts go out of the circle line they may hit the ground and increase the strain acting on them. Hitting with, for example, a pelvic rim in the beginning of a fall backwards can generate forces of inertia affecting particular body segments. These forces are especially dangerous to head, they can cause the head tilt backwards as in car accidents when the vehicle is hit at the back. The head movement is restricted by a headrest. In case of falling backwards there is no such a support, which may cause that the head hits the ground and get injured. Owing to the fact that particular body segments have different velocities during the impact, the body segments that were upper are more prone to impact. The most at risk of impacting is the head.

The biomechanical analysis of a fall should take into account the direction of the velocity with which a person hits the ground. If the vertical velocity component is significantly bigger than the horizontal one, for example during a fall from big heights, it is important to land on both feet at the same time. It results from the fact, that it is the key issue here that forces affecting hip joints are comparable. Only when this condition is satisfied we can proceed to roll over following a circle. On the other hand, with big values of the horizontal component of the fall velocity as compared with the vertical one, it is important to promptly assume the right position of the body so that the line of the body contact with the ground follows the circle. Under such circumstances the pelvis will not be injured because of unsymmetrical load of hip joints, when the value of the vertical velocity component during the impact is not big. Dangerous here are big velocity values reached by particular segments of a human body during an impact. This especially refers to head, which additionally obtains bigger velocity changes as a result of significant changes of the height on which it is located due to a fall as compared with other body segments. Some athletes during a fall intentionally increase their horizontal velocity component. This makes it easier to start rolling on a circle as shown in the film presented by National Geographic [44].

In the fall shown there the effect was a smaller contact force with the ground as compared with the dummy falling from the same height and having a smaller velocity during the impact. A simple experimental confirmation of the advisability of such a behaviour performed by athletes, is throwing a ball from a certain height onto the ground. If the direction of the ball velocity is close to vertical the ball first bounces off the ground several times and then starts to roll horizontally. Each ball bounce is a big strain during the impact. If we set the ball's velocity direction close to horizontal, the ball can proceed to rolling straightaway. This simple experiment justifies advisability of increasing the horizontal velocity component at the moment an athlete is contacting the ground in the presented film.

The biomechanical fall analysis made by the author of the present paper performed by rolling along the circle line is a certain addition to the biomechanical fall analysis made by Jaskólski and Nowacki [32]. In reality, when a person is falling during martial arts or combat sports competition it is not always possible to perform a full roll over along the circle line until the person can retake its standing position. In judo the opponent frequently hinders the move, therefore the falling person tries to reduce the energy of the impact. With *koho-ukemi* and *yoko-ukemi* falls [46] taught in judo, there rules the principle of hitting the ground with possibly the biggest body surface, simultaneously hitting the ground with the arm in order to reduce the impact energy. Martial arts and combat sports athletes often, in case there is a chance of a full fall following the circle and retaking the standing position, automatically hit the ground with the lower arm or hand to reduce the energy impact. This is because they are not certain whether the opponent will allow them to make a complete move following the circle and retake the standing position as a result of holding the grip.

The recently introduced to the Polish educational system [47] physical education curriculum acknowledges that the objective of physical education is to support physical, psychic and social development and health of pupils as well as to shape the habit of physical activity and health care throughout lifetime. The curriculum contains teaching programmes related to pupils' safe activity. However, the programmes stress pupils knowledge of causes of falls and injuries during physical activities. There is no focus on mastering practical skills increasing motor safety of a man such as practicing safe falls. Such classes are offered in Japanese schools where for many years judo has been a part of the school curriculum [1, 48].

In judo the basis for participation in competition is mastering the skill of safety falls. Thus, Japan is the country where the youngest group of the population is now covered by body injury prevention based on learning safety falls. So, there is a possibility, that death and body injury statistics caused by falls of elderly people in that country will be reduced significantly. Unfortunately, in Poland, despite so much work spent on showing the opportunities and effectiveness of the programmes teaching various age groups how to fall safely [25, 49-51], they have not been implemented yet, especially as part of compulsory physical education classes. In the majority of cases, the present educational systems do not perceive this phenomenon correctly. There are relevant, non-apparatus tests which make it possible to diagnose a degree of a man's motor safety during a fall. Furthermore, elaborating a proper apparatus for evaluating and teaching falling techniques could become an effective method of preventing injuries as a result of a fall. By improving falling techniques, it is possible to reduce injuries resulting from the impact. It is obvious, that reducing body injuries during a fall is possible only when external forces causing the fall that affect the man, can allow him to respond to a sudden disturbance of his balance. Exceeding certain values of those forces can cause, that the accelerations obtained by particular segments of a person's body when falling make any reaction impossible. However, often the situation of a falling man still provides for a certain reaction from him, for example, when slipping on an ice covered sidewalk. The most frequent with elderly people reasons for a fall 50% are slipping and stumbling [3, 52, 53].

In order to avoid falls, it is important to master the skill of maintaining balance at the moment of occurrence of the forces causing the fall. Also, it is important to master motor habits, which will make it possible to perform a certain motor activity allowing to assume the body position, which will reduce the strains affecting particular body segments during the impact when falling. The biomechanical knowledge presented in this article justifies the rightness of the statement, that "getting an injury" does not necessarily have to be an unavoidable consequence of a fall [24]. Body injuries can be reduced owing to a certain falling technique taken in particular physical circumstances causing it. The right falling technique is important for healthy people and it is also significant for the disabled with certain motor restrictions. With certain motor malfunctions there are greater risks of falling, thus it is necessary to teach the disabled in order to reduce the negative fall effects [54].

Conclusions

Summing up, it is right to undertake a range of experiments on increasing motor safety during falls. Such experiments would have a great utility importance. The author would set the following goals of such experiments:

1. Basing on the biomechanical knowledge of falls, determining the most efficient falling techniques that should be performed depending on the forces generating the fall.

2. Creating an apparatus to diagnose and improve falling skills.

3. Determining, by means of a special apparatus eliciting a fall, a degree of decreasing the proneness to body injuries owing to a certain falling technique.

4. Checking what training methods teach the right falling technique and increase man's balance level at the moment of the occurrence of forces causing the fall.

5. Improving training methods teaching the right falling techniques that improve the ability to keep balance at the moment of the occurrence of forces causing the fall, that could be introduced into the school educational programme.

6. Checking how practicing a certain sports discipline as well as age affect proneness to body injuries as a result of a fall and keeping the balance at the moment of occurrence of forces causing the fall.

Competing interest

The authors declare that they have no competing interests.

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