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Original Research

A model for potential non-contact ski injuries of the knee

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ABSTRACT

Broadly accepted is that most knee injuries result from increased vertical forces, usually induced by an incidental ski fall, collision, or a high jump. We present a new non-contact knee injury mechanism that can happen during a ski turn. Such an injury is governed by a sudden inward turn of the inner ski and consequent swing of the inner leg followed by a nearly instant stop when locked by hip and knee joints. The model provides predictive results for a lateral tibial plateau compression fracture because several simplifications have been made. We confirmed that the modelled compression stresses at typical skiing conditions and with typical skiing equipment can provoke serious knee injuries. The awareness of skiers and skiing equipment industry of the described knee injury mechanism can act as an important injury-prevention factor.

Introduction

Several studies indicate a slight decrease in the risk of lower extremity ski injuries over the last decade.[1] However, the proportion of knee injuries remains very high compared to the total incidence of ski injuries, e.g. in Norway, about 24% in the 16-year period 1996–2012[2], or in Japan, about 30% in the 18-year period 1996–2014.[3] During the last decade the skiing style has changed from conventional alpine skiing to carving skiing with increased risk for injury.[4] The reduction of knee injuries remains a main topic in alpine skiing injury prevention.[5] The compression fracture of the tibial plateau is one of the most severe of knee injuries. Tibial plateau fractures account for 0.52% of all ski injuries, and 3.4% of all ski-related fractures.[6] The risk of tibial plateau fractures has increased by 187% over 34 years from 1972/73 to 2005/06 season[1]; however, this change coincides with an aging of the population at risk, so that the trend over time could be associated with an increase in the mean age of the skiing population.[7,8]

According to a published cadaveric experimental study[9] hyperextension and valgus displacement were suggested to be the predominant and characteristic mechanism in 44% of all cases of tibial plateau fractures in recreational skiers on classic skis.[10] Other reported causes of tibial plateau fractures are falls from a height (improper landing), incidental falls or twists and the direct application of a force to the lateral aspect of the knee when hit by another skier. We hypothesise that a non-contact knee injury is possible that happens before the skier fall, or even with no fall at all.

The vertical forces produced during skiing[11] are at least for an order of magnitude smaller than critical forces reported in Ref. 9,12. A reasonable mechanism for developing the forces on the tibia is a sudden deceleration of the relatively heavy leg with the skiing equipment on a few centimetres displacement. Such a deceleration can appear during ski turn because of a momentary reduction in the turn radius while passing a snow brim or hollow depression,[13] or by hitting an obstacle on the skiing surface.

In this study a new mechanism of a non-contact knee injury is proposed with an application in alpine skiing, however, this mechanism is also applicable in other sports. The realistic injuries are in most cases combination of different mechanisms, e.g. fall, collision or jump. We focus on modelling of the biomechanics, based on a posterolateral rotation of a leg, boot and ski. The anatomy of hip and knee joints limits the rotation by certain angles that can suddenly decelerate the rotated parts. The inertial energy is relaxed through a relatively small joint bone area, which can produce its compression fracture. The model is not intended to provide exact results because several simplifications have been assumed, however, it demonstrates that also non-contact accidents can cause severe knee injuries.

Methods

The present study is a controlled observational laboratory study, based on actual injury cases and previously published measured data. In contrast to a classical perception of injuries where the skier is considered as a whole, here, we treat interactions between different parts of the body

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List of abbreviations

Acronyms and symbols

ILCG	inner leg's centre of gravity
CT	computed tomography
A	estimated area of depressed tibial plateau
β	angle between femoral and tibial axes after a fracture
ε	centre of rotation in the inner leg knee joint
Φ_C	final value of inner leg angle
E	inner leg rotational energy
F	compression force
J	inner leg angular momentum of inertia
L	inner leg length
m_1	mass of skier's upper part of body with an outer leg, ski and ski boot
m_2	total mass of inner leg with ski and ski boot
m_{21}	mass of upper part (femur) of inner leg
m_{22}	mass of lower part (tibia) of inner leg
m_{23}	mass of ski and ski boot
P	pressure
t	duration of fracturing
v_0	skiing velocity
ω	angular velocity
v_g	velocity of ILCG

SI units

kg	kilogram (mass)
kN	kilonewton (force)
MPa	megapascal (pressure)
m	meter (distance)
m^2	square meter (area)
m/s	meter per second (velocity)
rad	radian (angle)
rad/s	radian per second (angular velocity)

and ski equipment. The study procedures were approved by the institutional review board for research involving human subjects of the University Medical Centre Ljubljana and complied with the Helsinki Declaration. All volunteers signed a written informed consent prior to participating in the study.

Motivation

A motivation for the present work has been found in results of our previous two-year study[14] of 1065 ski injuries that have been treated at the surgical department of the University Medical Centre Ljubljana. We identified 33 (3.1%) fractures of the proximal tibia. Five of them (15%) were fractures of the medial, and thirteen of them (39%) were fractures of the lateral, condyle; the rest (46%) were combined fractures. All skiers' reports with tibial fracture have a common aspect. “The injury occurred while making a carving turn by a sudden pull of my inner ski, followed by a sharp pain in the inner leg knee.” Further motivation is in the fact that many non-documented and overlooked non-contact injuries, which often end just with pains and swelling or with ligament injuries,[15,16] could have the same injury mechanism. Fortunately, the acting forces are not strong enough for a compression fracture, but still sufficient for evident bone or ligament damages.

A computed tomography (CT) scan of a severely fractured knee is shown in Fig. 1, which evidences a 2.5×10^{-2} m deep depression (Fig. 1a) with an estimated area of depressed tibial plateau (A) of $3.7 \times 10^{-4}\,\mathrm{m}^2$ in the anterior part of the lateral tibial plateau (Fig. 1c). An analysis of the shape and location of the depression fracture of the tibia in the sagittal view (Fig. 1b) implied that only the posterior aspect of the lateral condyle of the femur could have caused the depression, and thus that the knee was in a semi-flexed position and the tibia was externally rotated at the time of injury. These assumptions agree with the patient's description of the injurious event.

We have deduced the following two hypotheses: (i) by injuries with no collision such large forces on the lateral tibial plateau cannot result just from vertical forces produced during skiing but should have another source. (ii) The approximate angle between femoral and tibial axes after a fracture (β), reconstructed from the CT scan is about $\beta = 0.52$ rad, which indicates an amount of lateral motion or swinging of the lower part of inner leg after the incident.

In order to isolate only the effects, which are important for the considered mechanism, several assumptions are made. Before the incident the skier is in a carved turn moving at a constant velocity. Skis are not sliding over the ground. We did not model the flexion of the inner knee before the injury because the proposed conceptual mechanism of the injury remains similar in an extended and a semi-flexed knee. We exclude collisions which can produce comparable forces as treated with our model. We do not take in consideration much smaller vertical forces resulting from skiing dynamics. For the sake of simplicity, we also

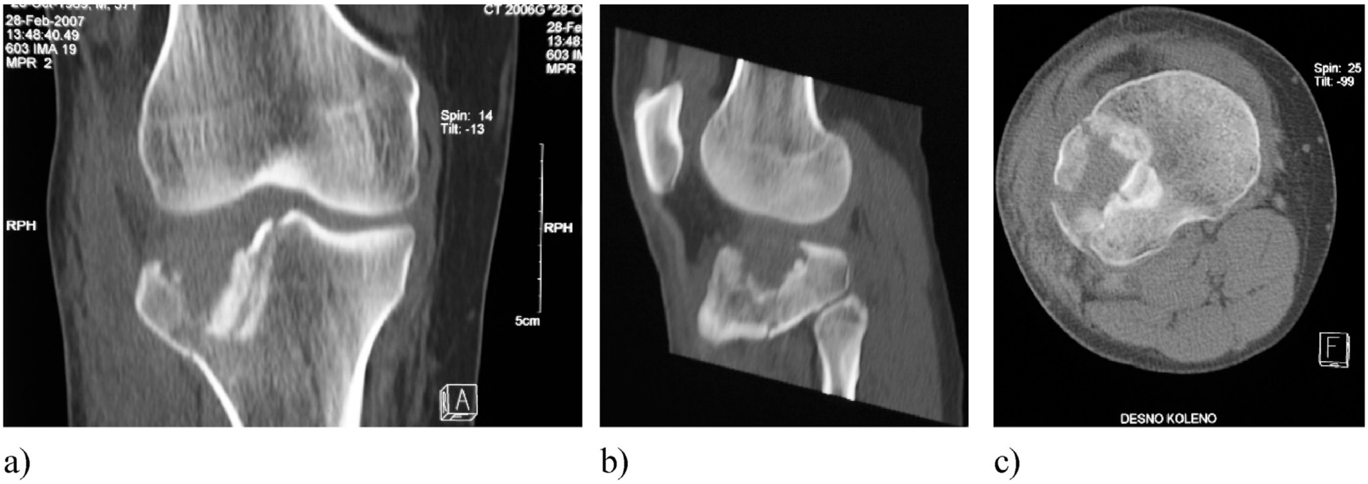

Fig. 1. Coronal (a), sagittal (b) and transverse (c) images of the right knee of patient with a lateral tibial compression fracture that occurred during a right carved ski turn, i.e. right inner ski. Image (a) was used for a determination of leg rotation constraints.

neglected energy losses due to the friction in joints and due to the deformation of tissues, as well as the effects of muscles.[12,17] Such assumptions affect the final results, however, we are looking for an explanation of the injury mechanism and not for the exact quantitative presentation of real case injuries.

Concept

The bulk part of the skier's mass represents the mass of upper part of body with an outer leg, ski and ski boot (m_1) and the mass of inner leg with ski and ski boot (m_2). The inner leg of length (L) is further divided into three parts – upper leg (femur) with mass (m_{21}), lower leg (tibia) with mass (m_{22}), and ski and ski boot with mass (m_{23}) – all with the total mass m_2. The inner leg parts can rotate along the centres of the hip and knee joints, while the ligaments and surrounding tissues, which are modelled as a single segment, lock both joints and stop them from experiencing excessive posterolateral rotations. We consider a swing of the inner leg in the posterolateral plane, therefore, it can be a subject of

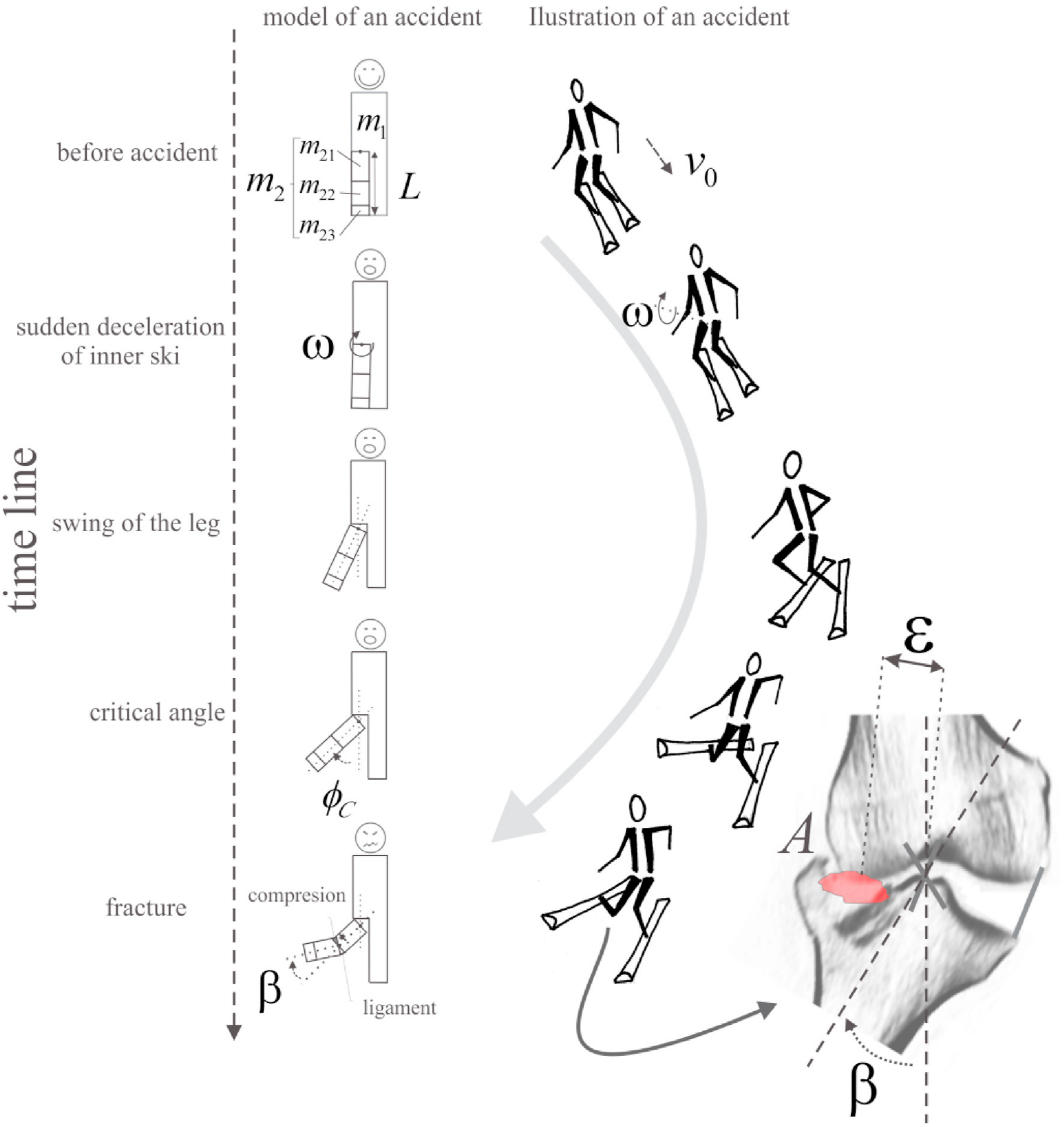

Fig. 2. The scheme of accident (illustration drawn by J. Polajnar) with the following abbreviations for model variables:
m_1 – mass of skier's upper part of body with an outer leg, ski and ski boot,
m_2 – total mass of inner leg with ski and ski boot,
m_{21} – mass of upper part (femur) of inner leg,
m_{22} – mass of lower part (tibia) of inner leg,
m_{23} – mass of ski and ski boot,
L – inner leg length,
v_0 – skiing velocity,
ω – angular velocity,
Φ_C – final value of inner leg angle,
β – angle between femoral and tibial axes after a fracture,
ε – centre of rotation in the inner leg knee joint,
A – estimated area of depressed tibial plateau.

angular momentum of inertia (J).

Before an accident, the skier is moving with a skiing velocity (v_0). At the moment when the inner ski decelerates, the inner leg begins to rotate around the hip joint axis with an angular velocity (ω). The rotation takes place until the final value of inner leg angle (Φ_C) when the ligaments and the surrounding tissues prevent any further rotation of the upper part of inner leg. The knee joint is now subjected to a significant amount of torque from the lower part of inner leg, which depends on the distance between the centre of depressed tibial plateau and the centre of rotation in the inner leg knee joint (ε). The accumulated energy is released in the lateral tibial plateau fracture, which stops the rotation at the final angle between femoral and tibial axes after fracture β. The key phases of the above-described accident, combined with all essential elements of the model, are illustrated in Fig. 2. An actual example of the described incident, recorded by coincidence, is shown in Fig. 3.

Model of non-contact injury mechanism

A more formal model, presented below, is based on the described concept and illustrated with the scheme of accident in Fig. 2. During the sudden deceleration of the inner ski we consider a system of equations for momentum and energy conservation, where v_0 is skiing velocity, v_g is velocity of inner leg's centre of gravity (ILCG), and ω is inner leg angular velocity:

$$v_0(2m_1+m_2)=2m_1\left(\frac{\omega L+2v_g}{2}\right)+m_2v_g+\frac{2J}{L}\omega, \tag{1a}$$

$$v_0^2(m_1+m_2)=m_1\left(v_g+\frac{L}{2}\omega\right)^2+m_2v_g^2+J\omega^2. \tag{1b}$$

The momentum of the inner leg's inertia is a sum of all separate momentum of inertia for upper leg, lower leg, and ski and ski boot with corresponding masses. If we assume that the ILCG is at $L/2$, the momentum J can be expressed as:

$$J=\left(\frac{1}{12}(m_{21}+m_{22})+\frac{1}{4}m_{23}\right)L^2. \tag{2}$$

The system (1) yields two solutions, the first is trivial:

$$v_g=v_0,\ \omega=0 \tag{3}$$

and the second is:

$$v_g=\frac{1}{2}\left(\frac{L^2(4m_1+3m_2)-4J}{L^2(4m_1+3m_2)+4J}-1\right)v_0, \tag{4a}$$

$$\omega=\frac{1}{L}\left(\frac{L^2(4m_1+3m_2)-4J}{L^2(4m_1+3m_2)+4J}+1\right)v_0. \tag{4b}$$

The inner leg rotational energy (E) at the moment just before the fracture is expressed as:

$$E=\frac{1}{2}J\omega^2, \tag{5}$$

with J and ω calculated from Equations (2) and (4b), respectively. We further assume that the deceleration is constant, which effectively means that the bone resists with a constant pressure (P) until the point of fracture. By considering the conservation energy, i.e. the energy E is equal to the work done during the deceleration ($\varepsilon\ \beta\ A\ P$), we get expression for pressure:

$$P=\frac{E}{\varepsilon\beta A}. \tag{6}$$

Results

We use the proposed model to validate the incident of case from Fig. 1. Using parameters from Table 1, we compute $\omega = 29.3$ rad/s from Equations (2) and (4b), and $P = J\,\omega^2/\,(2\ \varepsilon\ \beta\ A) = 177$ MPa from Equations (5) and (6). The duration of fracturing (t) can be estimated as $t = \beta/\omega = 0.018$ s.

In Fig. 4 The pressure P is shown as a function of the skiing velocity v_0 and the mass of ski and ski boot m_{23}. The red data point represents $P = 177$ MPa as obtained with data from Table 1. The horizontal red line at $P = 143$ MPa marks an average of measured ultimate compressive strength of the cortical bone that can cause a compression fracture of the lateral tibial plateau.[9,12,18,19] The black data point indicates that the ultimate compressive strength can be exceeded at skiing velocities higher than $v_0 = 13$ m/s with a typical mass of ski and boots $m_{23} = 6$ kg.

Discussion

Understanding injury mechanisms is a key component of preventing injuries in sport.[20–22] The mechanism of the lateral tibial plateau fracture due to a sudden deceleration of the inner ski is related to shaped skies and is added to other injury mechanisms described elsewhere.[23] The carving technique requires a weight distribution on both skies,[11] which allows, in some circumstances, the no-sliding assumption. If the ski edge is not sliding over the ground, ground forces are transferred directly to the leg. The skier's body moves in the direction of the ski turn. The decelerated ski can be interpreted as a posterolateral swinging relative to the skier's body. Here, we described the injury mechanism with a knee extended position, only. However, the same model can approximate also a semi-flexed knee position, which is more common during skiing.

Previously shown experimentally[9] that, without considering muscles acting on the knee joint at slow force loading rates (F/t), the typical axial force needed to provoke a tibial compression fracture is in the range of 13 kN–35 kN. Considering the estimated area of depressed tibial plateau $A = 3.7 \times 10^{-4}\,\mathrm{m}^2$ and skiing velocity $v_0 = 13.5$ m/s, we obtain the compressive stress $P = 143$ MPa. The resulting compression force (F) of

Fig. 3. Four video frames taken from a video sequence of a real incident recorded by coincidence.

Table 1
Set-up of the validated case with the following abbreviations for model variables and units:
m_1 – mass of skier's upper part of body with an outer leg, ski and ski boot,
m_2 – total mass of inner leg with ski and ski boot,
m_{21} – mass of upper part (femur) of inner leg,
m_{22} – mass of lower part (tibia) of inner leg,
m_{23} – mass of ski and ski boot,
L – inner leg length,
ε – centre of rotation in the inner leg knee joint,
A – estimated area of depressed tibial plateau,
β – angle between femoral and tibial axes after a fracture,
v_0 – skiing velocity,
kg – kilogram,
m – meter,
m^2 – square meter,
rad – radian (angle),
m/s – meter per second (velocity).

m_1 [kg]	m_2 [kg]	m_{21} [kg]	m_{22} [kg]	m_{23} [kg]	L[m]	ε [m]	A [m^2]	β [rad]	v_0 [m/s]
90	16.5	6.0	4.5	6.0	1	0.03	3.7×10^{-4}	0.52	15

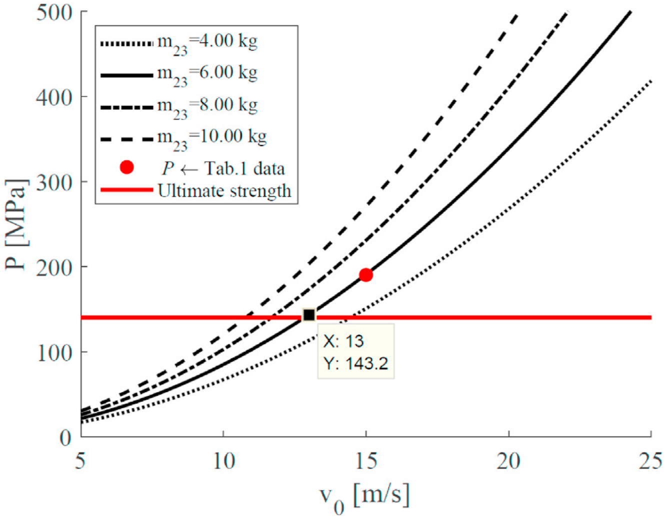

Fig. 4. Pressure on the lateral tibial plateau (P) as a function of the skiing velocity (v_0) and the mass of ski and ski boot (m_{23}). The red dot is the pressure $P = 177$ MPa obtained with data from Table 1. The red line marks the ultimate compressive stress 143 MPa that can be exceeded at v_0 higher than 13 m/s and can cause a compression fracture of the tibial plateau. SI units: kg – kilogram, MPa – megapascal, m/s – meter per second.

the proposed model is $F = A\ P = 53$ kN, which is higher, but in the same range, as experimentally determined data. The acting axial force could be higher if the knee joint is supported by the surrounding muscles, which act to distribute the forces and control movement. Additionally, the injury mechanism provides a fast force loading rates: $F/t = 53$ kN/0.02 s=2690 kN/s, which admits higher stresses[12] on the tibial plateau. Faster force loading rates could be a reason why the described compression fractures are relatively rare among trained competitors.[24]

Considering the model results, velocities higher than 10 m/s can generate a serious lateral tibial plateau fracture. Note, that the obtained results are taken as an estimate because the stiffness of a bone depends on bone density, shape, and the loading impulse. The bone is an anisotropic tissue with strength and hardness dependent on the direction of external forces. In general, the bone tissue may resist higher loads in the longitudinal direction, e.g. provoked by compression forces.[18,19] The bone is also viscoelastic, which means that it responds differently depending on the timing of the applied load.[25] These factors are important for determining the actual force needed for the fracture and are specific for each individual. On the other hand, the presence of osteoporosis could facilitate the crushing or depression of subchondral bone. The studied skiers had no history of osteoporotic fractures, but they belong to the age group at risk for tibial condyle fracture.[6,7] In younger skiers, the same mechanism might cause injury to medial or anterior ligaments. However, significantly different static and dynamic properties of bones and ligaments prevent us to draw definite conclusions about the impact of non-contact injuries on ligament damages.

Even though that the obtained results of this study are in accordance with previous experimental measurements we are aware that the model is not validated by actual measurements during incidents, which are rarely available. We used patients verbal recall of the incident for the purpose of describing injury mechanisms. However, the analysed skiers were experienced and aware of what was happening all the time, so their descriptions could be taken as reliable. For training and competition events videos could be available for study and analysis of injury mechanisms.[13]

The manufacturers of skiing equipment should further develop technical possibilities to reduce knee injuries[5] also by understanding the presented mechanism of the lateral tibial plateau fracture. Appropriate modifications on the skiing equipment design could reduce the injury risk. The increased mass of the ski and the ski boots contributes to the higher compression forces. The musculature, in particular the unloaded inner leg, should never be totally relaxed during ski turns in order to avoid uncontrolled skips of the ski. Recreational skiers should be cautious of their skiing speed and of any irregularity in the snow surface. Skiers should be aware that the smaller the radius of the ski edge, the bigger is the chance of an unexpected sudden lateral turn of the ski, so they should choose shaped skis according to their physical condition and skiing skill. The preparation of the ski slopes should be exact, not to leave ski brims and other irregularities, to avoid legal consequences.

Conclusions

The presented analysis and biomechanical model can explain a non-contact knee injury during ski turn with no fall or collision. The presented analysis suggests that a sudden inward turn of the inner ski and a subsequent swing of the inner leg is a possible mechanism of the non-contact knee injury, which worst case may result in the lateral tibial compression fracture. The obtained numerical results are in a close agreement with published preceding measurements. Many documented videos of accidents in recreational and competing skiers validate the proposed model. The clinical management of several actual injuries of recreational skiers and competitors also supports our findings. Most important is that professional skiers engaged in ski sports, and skiing equipment industry are aware of the presented non-contact knee-injury mechanisms in order to develop appropriate preventative measures.

Submission statement

The manuscript has not been published and is not under consideration for publication elsewhere.

Authors' contributions

Concept and initial model: TR; data acquisition and medical aspects: VM; injury model: KG; drafting manuscript: TR; revisions and comments: KG, VM, TR; final approval of manuscript: KG, VM, TR.

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Ethical approval

The study procedures were approved by the institutional review board for research involving human subjects of the University Medical Centre Ljubljana and complied with the Helsinki Declaration. All volunteers signed a written informed consent prior to participating in the study.

Conflict of interest

All authors confirm that no potential conflicts of interest are to be declared.

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