Mathematical model of the energy absorbing stitch brake used in via ferrata climbing

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Abstract

Via ferrata climbing become more and more popular, but currently no appropriate safety equipment is available for lightweight climbers. The only criterion to get a safety certification for an energy absorbing system is to fulfill the safety requirements specified in European standard EN 958 for an 80 kg mass. But in case of a fall, the braking force which is necessary to full the existing European standard results in high decelerations on lightweight users. Therefore a modification of the standard had to be carried out. The goal of this study was the development and validation of a mathematical model of the energy absorbing systems for analyzing injury risks for lightweight people.

A model of the energy absorption technology was developed using the multi-body simulation software SIMPACK. In tension the force element starts with a reversible deformation and switches to irreversible deformation when a maximum elastic force is reached. During the rebound only the elastic deformation is reversed whilst the plastic deformation remains. For the validation of the model comparisons with experimental tests according to standard EN 958 were carried out using iron masses of 34 kg, 48 kg, 77 kg and 80 kg. The simulation results showed a good accordance with the experimental data, e.g. the irreversible deformations differ with 9.5 % for 34 kg, 1.6 % for 48 kg, 5.1 % for 77 kg and 3.3 % for 80 kg. With the developed model realistic falling situations will be analyzed and an optimization of the safety equipment with a modification of the standard can be established.

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Keywords: Climbing; via ferrata; computer simulation; multi body system; EN 958; energy absorbing system

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1. Introduction

Via Ferrata climbing has become increasingly popular by families with children, but there is currently no specific safety equipment available for child use and the existing safety equipment for adults are not secure enough for child use.

According to the European standard EN 958: “Mountaineering equipment – Energy absorbing systems for use in Klettersteig (Via Ferrata) climbing” a maximum force of 6 kN is reasonable to a climber [1]. Experiments with crash test dummies carried out by the Safety Research of the German Mountaineering Club (Deutscher Alpen Verein DAV) showed that none of the via ferrata sets currently available on the market are suitable for persons with less than 50 kg body weight. In case of a fall, the braking force which is necessary to fulfill the existing European standard results in high decelerations on lightweight users [2].

Functional energy absorbing systems show responding values between 3.5 kN and 4.5 kN. With forces within this range the equipment system decelerates the downfall by absorbing the kinetic energy. Following the second Newton law of motion the acceleration $a$ of a body is parallel and directly proportional to the net force $F$ and inversely proportional to the mass $m$, i.e.,

$$F = ma$$

(1)

With a constant responding value of 4.5 kN the deceleration value for an adult with a body mass of 75 kg results in a 6-times gravitational deceleration compared to a 15-times gravitational deceleration for a child with a body mass of 30 kg.

A modification of the equipment for children is not possible because the only criterion to obtain a CE safety certification is to fulfill the safety requirements specified in European standard EN 958: “Mountaineering equipment – Energy absorbing systems for use in Klettersteig (Via Ferrata) climbing”. Within this test procedure a falling mass of 80 kg and a drop height of 5 m are specified for calculating the shock absorption capacity and the slowing-down length of energy absorbing systems (fig. 1).

![Fig. 1. Test set-up according to EN 958 [1]](image)
Two types of brake are used in energy absorbing systems:

A metal plate brake through which a rope is passed providing a high degree of resistance. This technique allows the climber to re-thread the rope in case of a fall allowing them to have some degree of protection while completing the climb.

A stitch brake which progressively tears in case of a fall, providing a gradual slow down and therefore is certified for only one fall. The system may be so lengthened after a fall as to be unusable, but it is easy to verify that the device has been deployed.

The goal of this study was the development and validation of a mathematical model of a stitch brake which can be used for more detailed investigations of the injury risk of via ferrata falling situations for lightweight people as base for a modification of the EN958.

2. Model description

2.1. Energy-absorption lanyard - Stitch brake model

The developed stitch brake model is based on an elastic-plastic spring model included in the multi-body simulation software SIMPACK (SIMPACK AG, Gilching, Germany) [3]. The used model of the stitch brake includes an elastic and a plastic part in tension direction. In the first loading part, the model starts with an elastic, i.e. with a reversible deformation. When the maximum elastic force is reached then it switches to plastic, i.e. to an irreversible deformation. During the rebound only the elastic deformation is reversed whilst the plastic deformation remains. Due to the remaining plastic deformation the point where it changes from compression and tension or vice versa change during the simulation.

Figure 2 shows an example for the behavior of the element. It shows two complete deformation cycles with decreasing amplitude. The elastic and plastic sections are marked by numbers. The elastic rebound forces are scaled by the factor 0.5 with respect to the elastic deformation forces.

![Fig. 2. Description of the energy-absorption lanyard [3] - stitch brake model](image-url)
2.2. Experimental tests

In order to test the behavior of the climbing sets, the test set-up prescribed in EN 958 was modeled as Multi Body System including the described stitch brake model.

For the validation of the stitch brake model comparisons with experimental tests carried out by the Safety Research of the German Mountaineering Club (Deutscher Alpen Verein DAV) according to standard EN 958 were carried out. But other than specified by the standard the test series were now carried out by iron masses of different weights to determine the influence of the mass on the impact and the slowing down length. Based on the up-to-date anthropometrical database of Size Germany [4] different masses were specified as representatives for normal weight and lightweight users (77 kg (50th percentile male), 48 kg (5th percentile female), 34 kg (5th percentile male – 11 to 13 years).

3. Results

Figure 3 shows the resulting forces of the simulation results and the experimental data and figure 4 the resulting irreversible deformations for the test with the iron masses of 34 kg, 48 kg, 77 kg and 80 kg. For both parameters a very good accordance of the simulation results and the experimental data was shown. The irreversible deformations differ with 9.5 % for 34 kg, 1.6 % for 48 kg, 5.1 % for 77 kg and 3.3 % for 80 kg.

Fig. 3. Resulting forces: experiments (continuous lines) vs. simulation (dotted lines)
4. Conclusion

With the comparison of the experimental test results and the computer simulation results it was verified that the developed mathematical model of a stitch brake can be used for more detailed investigations of the injury risk of via ferrata falling situations. With the existing tools it has to be analyzed in which way the safety requirements specified in European standard EN 958: “Mountaineering equipment – Energy absorbing systems for use in via ferrata climbing” have to be modified to for lightweight users.

5. Further research

Therefore analyses are carried out using human models - experimentally by using crash test dummies and computer simulations using human MBS models - to gain more detailed information of the resulting injury risks (e.g. head accelerations). For the computer simulation of a via ferrata fall a 15 segment parameterized human MBS is developed based on the anthropometrical database of Size Germany (fig. 5a). For the calculation of the specific injury risk in the soft tissue structures a detailed head-neck model will be integrated in the MBS in a further development (fig. 5b). Corresponding 3D surface models - based on CT data of vertebras (T3 to C1), ribs, clavicle, sternum and cranium - were created describing the exact bone geometries. Implementation of user routines allows the modulation of force elements describing the material behavior of human soft tissue structures such as ligaments, tendons, and cartilage layers. The viscoelastic behavior of each soft tissue structure was calculated as a function of the geometry, loading velocity and the current strain situation. All force elements were validated by tensile tests [5].
Fig. 5. (a) Simulation of a via ferrata fall using a 15 segment man model; (b) Detailed MBS of head, neck, cervical spine

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