The effects of different figure skating boots on the human body during the landing impact.

- A comparison between two figure skating boots, Edea and Graf.

Ondrej Spiegl
ACKNOWLEDGEMENTS

First and foremost I am very grateful to my supervisor, Professor Toni Arndt, for his expert guidance and valuable advice throughout this project.

To Olga Tarassova, thank you for your professional guidance during the measurements in the Biomechanics and Motor Control (BMC) laboratory.

Thank you to Julio Cézar Lima da Silva and Tiago Jacques for the assistance in the research and for the valuable tips as well as to Anja Zoellner for the correction of many grammar mistakes in my text.

To the skaters who participated in the research, thank you for your time and willingness. Also a huge thanks to Basset Blades, Graf Skates AG, Nordic Ice Consulting AB and Teijas Skateshop AB for providing all the necessary equipment to conduct the research.

And finally I never could have done this project without the support and smiles of my girl friend Moa Lindgren.
Abstract

Aim: The purpose of this research was to investigate the effects of different figure skating boots on kinetic and kinematic properties of the landing impact. The focus was on the vertical ground reaction force (VGRF) and kinematic differences between the examined boots during the landing impact as well as the material and construction design differences between the boots.

The hypothesis was that different figure skating boots (Graf Edmonton and Edea Concerto) differently affect the VGRF and kinematics during the landing impact so some figure skating boots may reduce the impact at landing and could therefore possibly prevent injuries.

Method: Six subjects each simulated figure skating landings wearing two different types of skates from two different heights, on artificial ice. Differences were investigated between the boots in angular position of individual body segments and in the VGRF that acts between the skate and a force platform underneath a plastic ice surface, as well as the force which acts between the skate and the foot. The landings were examined with a Pedar-X in-shoe pressure measuring system, a Kistler force plate and a Qualysis motion capture system. The obtained values of each variable were statistically compared between the boots using SPSS.

Results: Statistically significant (p≤0.05) differences between the boots were seen in the degree of right ankle and knee joint flexion during the initial landing impact, in the degree of right ankle joint peak flexion, as well as in the force magnitude experienced by the right foot during the landing impacts as well as for the area under the max force-time curve. Furthermore, differences were seen in the construction design, materials, sizes of the outsole and in the stiffness.

Conclusions: This research suggests there are differences in lower extremity VGRF and kinematic effects of landing impact when using different boots. It also suggests that some figure skating boots reduce the loading on the human body during the landing impacts more than others and therefore could help in preventing injuries.
Table of contents

1. Introduction .......................................................................................................................... 1
   1.2 Injuries in figure skating ................................................................................................. 3
   1.3 Figure skate .................................................................................................................... 4
   1.4 Assessment of landing in general .................................................................................... 5
   1.5 Different approaches to research in figure skating ......................................................... 9
   1.6 Purpose, research question and hypothesis .................................................................. 11
2. Methods ................................................................................................................................. 13
   2.1 Research procedure and data collection ......................................................................... 14
   2.1.1 Analysis of skating boots ......................................................................................... 14
   2.1.2 Subjects and ethical aspects .................................................................................... 15
   2.1.3 Jump landing simulation .......................................................................................... 16
   2.1.4 Experimental procedure .......................................................................................... 17
   2.1.4.1 Specification of measuring systems ...................................................................... 19
       2.1.4.1.1 Pedar X ......................................................................................................... 19
       2.1.4.1.2 Kistler force plate ......................................................................................... 20
       2.1.4.1.3 Qualisys motion capture system .................................................................. 20
   2.1.5 Data Analysis ............................................................................................................ 20
3. Results .................................................................................................................................. 22
   3.1 Results from the analysis of skating boots ..................................................................... 22
   3.2 Kinematic and VGRF results ......................................................................................... 23
   3.3 Statistically significant differences in VGRF ................................................................. 23
   3.4 Statistically significant differences in kinematics ......................................................... 27
4. Discussion .............................................................................................................................. 30
   4.1 Limitations ...................................................................................................................... 32
       4.1.1 Simulation of jumps in a laboratory setting ............................................................... 32
       4.1.2 1st peak flexion in kinematic analysis ...................................................................... 33
       4.1.3 Pressure data .......................................................................................................... 33
       4.1.4 Sampling frequencies .............................................................................................. 33
       4.1.5 Boots and blades ..................................................................................................... 33
       4.1.6 Subjects .................................................................................................................. 34
       4.1.7 Error of Pedar-X insole .......................................................................................... 34
       4.1.8 Human body models for kinematics analysis .......................................................... 35
4.1.9 Time to peak variables from force plate data ........................................... 35
4.2 Future research ............................................................................................... 35
5. Conclusions ...................................................................................................... 36
References ........................................................................................................... 37

Appendix 1. Literature research
Appendix 2. Kinematics, VGRF, Figure skating boots

**Table and figure contents**

Table 1 – Individual distance between box and force plate................................. 16
Table 2 – Comparison of figure skating boots ..................................................... 22
Table 3 – An overview of the average values of all subjects for all particular force variables. .............................................................................................................. 26
Table 4 – An overview of the average values of all subjects for all particular kinematic variables ........................................................................................................ 29

Figure 1 – Descriptive picture of a figure skating boot....................................... 5
Figure 2 - The Graf and Edea figure skating boots and Jackson blade ................. 13
Figure 3 - Artificial ice surface in the laboratory ................................................ 16
Figure 4 - Illustrative picture of the figure skating boot ..................................... 22
Figure 5 – Division of the foot ........................................................................... 23
Figure 6 – Force-time curve, illustrating the variables investigated in this study .......... 24
Figure 7 – Significant differences in VGRF variables between the Graf Edmonton and Edea Concerto boots where each value for the subject represent the average of six trials........... 25
Figure 8 – Pedar- area under the max force-time curve (rearfoot section, 50 cm BOX)........ 26
Figure 9 – Joint angles presented in the kinematic figures .................................. 26
Figure 10 – Significant differences in kinematic variables between the Graf Edmonton and Edea Concerto boots where each value for the subject represent the average of six trials...... 28
1. Introduction

Physical activity is an irreplaceable component of daily life. However, elite sport as a form of physical activity places increasingly higher goals which can come at the expense of athletes’ health. Continuously forward moving boundaries of human achievement in sport as well as increasing competition in races puts pressure on athletes to push their limits. This also applies to figure skating performances which have changed a lot during the last 25 years.

Figure skating is a sport that combines athleticism and artistry. There are four disciplines in figure skating: singles skating, pairs skating, ice dance and synchronized skating. Until 1991 skaters practiced and competed in so-called compulsory figures and free skating (Šťastná-Königová 1985). When the International Skating Union removed the compulsory figures from the competitions, skaters started to spend more time practicing free skating (Shulman 2002; Bruening & Richards 2006). That meant, among other things, practicing more jumps, which are one of the key elements of both singles and pairs skating (Porter et al, 2007).

Jumps are composed of horizontal movement with constant speed, and movement vertically upwards and backwards in free fall. Taking into account drag, the trajectory has the shape of a ballistic curve. Another essential component of figure skating jumps is the rotational impulse. The landing of the jump should be smoothly executed through the toe picks to the edge of the blade. Properly executed jump must be robust, i.e. high and long with a quick vertical rotation (Dědič 1979; Fassi, Smith & Stark 1980).

Over the last few years figure skating has become more popular and the participation in this sport has more than doubled (Bradley 2006). Incredible progress in the complexity of elements has been made. Triple jumps, which were enough to win the world championships in senior categories several years ago, are now performed by skaters of lower categories. Success in today’s competitive figure skating, in singles and pairs, is mainly dependent upon the number of triple and quadruple jumps that the skater can successfully land in competition. Therefore the pressure on solo figure skaters to jump higher and manage a greater number of rotations in the air increases.

To keep up with the competition, figure skaters are increasing the intensity of their training, performing a greater number of jumps than they would have in the past. A solo skater can perform 50-100 jumps a day, six days a week through the season and off season (Bruening & Richards 2006). Covered ice rinks, which are often available throughout the year permit skaters to practice continuously for the whole year. These changes have resulted in an
increased number of injuries in figure skaters. Devoting more time to free skating means performing more jump elements exposing the body to forces during the take-off and landing (Porter et al. 2007). A large number of landing repetitions of multiple rotation jumps and absorbing of high ground reaction forces may result in various injuries (Dubravcic-Simpanjak et al. 2003; Fortin & Roberts 2003; Bruening & Richards 2006; Ortega, Rodriguez Bies & Berral De La Rosa 2010). However the severity and magnitude of the present situation is not sufficiently well documented in current literature and research (Bradley 2006).

During each jump landing, the figure skater impacts the ice with a certain force, which is counteracted by an equal and opposite force applied by the ice back on the skater, which travels through the figure skating boot to the lower-extremity and continues to other body segments (Larson 2011; Cong 2012). This force is known as the vertical ground reaction force (VGRF). Depending on the type of landing (for example toe to heel landing or landing on the whole foot), VGRF can be characterized by one or two high transient peaks, which last only a few milliseconds (Bruening & Richards 2006). The VGRF which affects the skater during the landing can be as high as six times body weight (Acuña et al. 2014).

The current ice skate design limits the ability of the human body to absorb impact forces during jump landings, due to the restriction of ankle motion in the sagittal plane (Bruening & Richards 2006). The landing impact creates a shock wave which acts on the ankle, knee, hip and back and can be the cause of excessive strain and load which can lead to the development of overuse injuries (Dubravcic-Simpanjak et al. 2003; Bruening & Richards 2006; Campanelli et al. 2015).

As mentioned by Saunders et al. (2014), there are not many studies which are focused on reduction of VGRF during the landing impact. Insight into how different skating boots influence landing VGRF and kinematics is important for finding options for how to prevent injuries, especially when jumping in skating boots is performed daily (Oliver et al, 2011). The current research will be focused on examining VGRF and kinematics during the landing impact in different figure skating boots and will try to identify whether any of the tested skating boots reduce the impact force that the skater must absorb and therefore possibly reduce the risk of injury. Unlike the increasing performance in figure skating, the design of skating boots has changed minimally, therefore such an outcome would be useful when designing new skating boots (Bradley 2006; Bruening & Richards 2006).
1.2 Injuries in figure skating

Over the last few years the number of overuse injuries in figure skaters has increased, which is mainly attributed to an increased volume in jump training (Bruening & Richards 2006). Another cause of the increased number and frequency of injuries is a greater number of participants in the sport, which has more than doubled since 2006. As the number of figure skating participants increases, so will the number of active patients (Bradley 2006). The number of injuries differs between age categories and disciplines of figure skating (Fortin & Roberts 2003). The repetitive trauma of landings and take-offs induces strain in the hip, ankle, knee and lower back of the skater (Porter et al. 2007; Weinhandl, Smith & Dugan 2011; Charles 2015). The sum of the excessive forces and moments, which acts on the human body, result in loads which can cause micro or macro damage of anatomical structures, and may lead to overuse injuries (Nash 1988; Nigg & Bobbert 1990; Zhang, Bates & Dufek 2000; Fortin & Roberts 2003; Acuña et al. 2014; Saunders et al. 2014; Charles 2015). Van Der Worp et al. (2014) suggest that the risk of injury also increases with reduced range of motion of joint flexion angles and high joint angular velocities during landing.

The amount of stress and increased risk of traumatic injuries depends on a skater's volume of skating, workout routine and impact forces which increase with both the number of vertical rotations in a jump and with jump height (Lockwood & Gervais 1997; Bradley 2006; Porter et al. 2007; Dubravčić-Šimunjak et al. 2008; Yeow, Lee & Goh 2009; Ortega, Rodriguez Bies & Berral De La Rosa 2010; Acuña et al. 2014; Saunders et al. 2014). More than 50% of injuries among young soloists are caused by a training overload (Dubravčić-Simunjak et al. 2003). The most common chronic overuse injuries experienced by figure skaters are inflammation of the Achilles tendon (Achilles tendinitis), stress fractures, bone marrow lesions, patellar-femoral pain syndrome ("jumper's knee"), patellar tendinitis, anterior cruciate ligament (ACL) injuries and injuries to the lumbar spine and hip (Fortin, Harrington & Langenbeck 1997; Kho 1998; Dubravčić-Simunjak et al. 2003; Yeow, Lee & Goh 2009; Van Der et al. 2014).

Other injuries of the lower limbs are caused mainly by the everyday wearing of the figure skating boots that expose the foot and ankle to pressure. These problems are most common in competitors and the main cause is the rigidity, the shape of the boots and the height of the heel. The most common injuries are bursitis (inflammation of the bursa) in the ankle joints, ankle sprain, inflammation of the Achilles tendon, heel bone deformation, bunion, calluses, hammer toes, blisters. (Dubravčić-Simunjak et al. 2003; Bradley 2006; Cong
2012; Campanelli et al. 2015). The rigidity of boots may also result in weakness and shortening of the muscles around the ankle (Porter et al. 2007; Saunders et al. 2014).

According to the studies of Bradley (2006) and Fortin, Harrington & Langenbeck (1997), for the accurate diagnosis, treatment and prevention of these injuries it is important to have knowledge about the skater’s workout routine, the demands of figure skating sport, but also about the figure skating boot design.

1.3 Figure skate

Figure skates are the most important piece of equipment for figure skaters. With gradual development of skates and with the beginning of modern skating history, skating acquired a sportier character. Skates became individually developed for different disciplines such as hockey, speed skating and figure skating.

There are minor and major differences between different modern figure skates (figure 1). Often the boots are made of several layers of leather or other material. Each manufacturer produces a different boot construction. They use different heel height, materials and different manufacturers also use different sizing charts (Bradley 2006; Campanelli et al. 2015). Various boot models are available, with different degrees of stiffness according to figure skating discipline, skater quality, age, and weight. The boot stiffness contributes to the securing of the ankle joint, to prevent excessive motion in the frontal plane (Cordova et al. 2010; Campanelli et al. 2015; Rowley & Richards 2015). For example, ice dancers, who do not expose the boots to much impact, would rather choose softer boots compared to single skaters, who expose the boots to landing impacts many times during a day. On the other hand, the stiffness of the boot and the raised heel limits the ankle range of motion, which significantly limits the knee joint range of motion, work output and therefore also limits the jump height (Dubravcic-Simunjak et al. 2003; Haguenauser, Legreneur & Monteil 2006; Robert-Lachaine et al. 2012; Saunders et al. 2014).

Competitors are choosing boots and blades separately according to individual needs. The blade has a width of 3-4 mm, is curved along its entire length, and has toe picks whose number and shape vary according to the skating discipline. They are made of high quality steel and recently also of a variety of lightweight materials. Blade length is also different for ice dancers and singles skaters. The blades are mounted on the outsole with screws, so that the blade’s longitudinal axis coincides with the longitudinal axis of the outsole.
1.4 Assessment of landing in general

Jumps and landings are an essential part of many sports and are studied by many researchers and by various methods. The human body is exposed, during each landing impact, to a certain force that places high mechanical demands on the joints and tissues (Devita and Skelly 1992; Decker et al 2003; Schmitz et al. 2007; Weinhandl, Smith & Dugan 2011). The deceleration of the mass during the impact is complicated, because the human body is divided into individual segments and each segment can play a different role during the deceleration (Bobbert, Schamhardt & Nigg 1991).

Research of landing biomechanics includes examination of kinematics (such as angular position of individual body segments), kinetics (such as VGRF variables) and muscle activity. Factors of importance are whether it is a drop landing or if the landing is from a countermovement jump, if a person lands on one or two legs, on what surface, from what height, and with what technique. The most common methods of research are via force plate, special insoles which measure forces and pressure, video cameras and by electromyography.

During landing the joints of the lower extremity are rapidly flexing and muscles are eccentrically contracting to resist the impact forces and to partly dissipate high energy that would otherwise fully hit the supporting tissues such as cartilage, ligaments and bones (DeVita and Skelly 1992; Yeow, Lee & Goh 2009; Norcross et al. 2013). The force
which acts on the body during the landing impact may be as high as six times body weight (Oliver et al. 2011; Acuña et al. 2014).


With increasing height and landing stiffness the peak VGRF, peak joint moments and power increase (Zhang, Bates & Dufek 2000; Yeow, Lee & Goh 2009). Lockwood, Baudin & Gervais (1996) have observed two distinctly different landing techniques, hard landing and soft landing. During soft landings the force which must be absorbed by the body is smaller, but acts for a longer period of time. On the other hand, during hard landings greater force is produced, but the duration of this force is decreased. Due to the short duration of greater force during the hard landing impacts, the human body is exposed to a greater risk of injury. Obvious differences between hard and soft landings are in greater contribution of plantar flexors during hard landings, whereas for deceleration during soft landings and increased landing height the main contributors are the hip and knee extensors (Devita & Skelly 1992; Zhang, Bates & Dufek 2000; Yeow, Lee & Goh 2009).

Although the ankle plantar flexors are the first to absorb the impact force, they have not been identified as a main contributor for energy dissipation. In determining the major contributor for energy dissipation, previous results vary. Zhang, Bates & Dufek (2000), Decker et al. (2003), Weinhandl, Smith & Dugan (2011) and Norcross et al. (2013) have identified the main contributor of energy dissipation to be the knee extensor, while Yeow, Lee & Goh (2009) have identified the hip extensors as the top contributor to energy absorption. A possible cause for this variation could indicate a different landing strategy in the frontal plane being used by participants in the studies. Podraza & White (2010) reported greatest VGRF magnitudes during the landing when the knee had between 0 to 25 degrees of flexion and under these conditions the knee had to withstand much quicker changes in kinetic energy.

The angular position of individual body segments, especially of the lower extremity segments at initial ground contact (IC) are important determinants of both VGRF variables and energy dissipation. Because the ankle is the first significant joint in the kinematic chain which is exposed to the impact during landing, it determines the position of other body segments (Bruening & Richards 2006). Also, depending on the jump height and
landing technique, the motion and time sequencing of individual body segments changes and thus the contribution of individual body segments in force dissipation and absorption also changes (Mcnitt-Gray 1993; Zhang, Bates & Dufek 2000; Hou et al. 2005; Kulas, Windley & Schmitz 2005; Yeow, Lee & Goh 2009; Weinhandl, Smith & Dugan 2011; Koh et al. 2012; Norcross et al. 2013; Rowley & Richards 2015; Sorenson et al. 2015). Landing with greater ankle plantar flexion during the landing impact has demonstrated the best shock absorption strategy with reduced the peak VGRF and loading rate (Self & Paine 2001; Rowley & Richards 2015).

It is not always possible to examine landings of athletes from different jumps in natural conditions. Researchers are often limited by the technical equipment and measuring instruments, therefore it is often necessary to carry out testing in the laboratory, where various jumps and landings must be simulated. The most common simulation of a regular countermovement jump landing is a drop landing from a box with a predefined height. Unfortunately, there is a difference in landings performed from a countermovement jump compared to drop landings (Afifi & Hinrichs 2012; Chiu & Moolyk 2015). Afifi & Hinrichs (2012) Chiu & Moolyk (2015) have suggested that subjects were better prepared for the landing impact from a jump with countermovement as opposed to stepping off a box (drop jump) conditions, which was due to the activation of the muscles at the instant of take-off. This was also confirmed by electromyography, which showed greater muscle activity during the countermovement jump conditions. Although it was predefined from which height the subjects would perform the landings, it turned out that some participants lowered their center of mass before stepping off the box and therefore drop from a different height to what the box actually was. The touchdown velocities can therefore vary between each trial (Afifi & Hinrichs 2012). There is also a difference between landing from a vertical jump and landing from a forward jump, which is preceded by a forward acceleration. During the landing from a forward jump, not just vertical, but also a horizontal deceleration must be achieved and this is the reason why during this impact there is a higher peak GRF compared to vertical jump landing (Edwards et al. 2012; Van Der Worp et al. 2014).

Several researchers have investigated the influence of footwear on the force produced during the landing impact. The ability of shoes to absorb shock and a certain amount of GRF during the impacts is important for the prevention of injuries (Cong 2012). Medial arch support in a shoe with the firm heel outer, high lacing and stiff upper can protect the foot from abnormal movement by controlling the initial heel contact position and providing an optimal coupling relationship between the foot and the knee (Özkan 2005; Cong
Because the transmission of initial impact force is affected and can be partly absorbed by the mechanical properties of the shoe, it is important to consider the structure, sole design and material. The material used in the shoe does affects not just the capacity of force absorption but it may also affect the movement pattern of individual body segments. Therefore a shoe structure and design can prevent injuries by damping the shocks, absorbing the VGRF and controlling the motion (Cong 2012).

Researchers have also compared kinematics and VGRF during landings in males and females (Decker et al. 2003; Wojtys et al. 2003; Salci et al. 2004; Schmitz et al. 2007). These studies gave conflicting results. Some have found differences among males and females while others have not. Greater peak VGRF in females was reported in Schmitz et al. (2007) and Salci et al. (2004) whereas no differences between male and female in peak VGRF were observed in the research of Decker et al. (2003). On the other hand, Decker et al. (2003) observed differences between females and males in kinematics at IC, with females landing in a more erect position and utilizing a greater hip and ankle joint range of motion and higher joint angular velocities compared to males. Schmitz et al. (2007), who also observed differences in kinematics reported, that females used less total hip and knee flexion and had shorter time to peak flexion compared to males which indicates an ankle dominant strategy by females.

As exposure to high forces and to high instantaneous and average loading rates during the landing impact is linked with high injury risk, the goal of many studies was to explore a way in which to optimize the landing impact and to prevent injuries. Bruening & Richards (2006) concluded that peak heel impact VGRF can be decreased by decreasing the heel deceleration magnitude or by controlling the mass that is decelerated at the heel strike, but also by some combination of these mentioned options. Increased range of motion in the joints of body segments during the impact, especially during the first 100 milliseconds after the initial contact with the ground until the minimal vertical position of the center of body mass, is an important factor in reduction of the force, because the impact force can be spread out over a longer period of time (Dufek & Bates 1990; Devita & Skelly 1992; Hou et al. 2005; Bruening & Richards 2006; Norcross et al. 2013;). Also, instructing the subjects to change the magnitude of motion through knee flexion during the landing can lead to a reduction of the peak GRF because the muscular system will be better prepared to absorb some of the kinetic energy (Devita & Skelly 1992; Ericksen et al. 2013; Norcross et al. 2013). Finally, appropriate footwear plays an important role in protecting the foot, joints and spine during the impact. Delaying the peak impact force and prolonging the impact duration,
inhibiting high peaks and shock frequencies and a good redistribution of pressure under the foot are important factors of footwear that contribute to injury prevention (Cong 2012).

1.5 Different approaches to research in figure skating

Several studies have been conducted in order to identify the forces and angular positions of individual body segments during the takeoff and landing of figure skating jumps. The existing research has a high significance for the current study and for future studies referring to figure skating (Foti 1990; King, Arnold & Smith 1994; Albert & Miller 1996; Kho & Bishop 1996; Lockwood, Baudin & Gervais 1996; Lockwood & Gervais 1997; Kho 1998; Bruening & Richards 2006; Haguenauer, Legreneur & Monteil 2006; Lockwood, Gervais & McCrea- 2006; Acuña et al. 2014; Saunders et al. 2014).

The aforementioned research was devoted to figure skate design, VGRF and kinematics. Several studies have evaluated the impact forces and lower extremity angular position during the landing from a jump. The studies generally tend to conclude that the figure skates are not optimally designed for jumping. Therefore, not only King (2008) but also Bruening & Richards (2006) proposed that the research related to figure skating and to figure skating boots should henceforth continue and, by utilizing new materials and technologies, come to a proposals on how to prevent the increasing number of accidents and injuries.

Examining VGRF and kinematics of figure skating jump landing is not easy because certain measurement approaches can interfere with the performance of the skater. Several studies and measurements were conducted in biomechanical laboratories, others were conducted on the ice rink. Some of the studies used a combination of both approaches. Both the laboratory measurements and the measurements on the ice rink had certain limitations. The biggest challenge and limitation during the research measurements on the ice rink was the positioning of video cameras and the impossibility of using the force plate due to the technical difficulty of its positioning under the ice surface. On the other hand, the conditions for the skaters and the jumps are most optimal.

During research in the biomechanical laboratory, the force plate can be firmly positioned in the floor, several video cameras can be located at different angles and all systems can be synchronized, however it is difficult to imitate the ice rink environment. The laboratory is mostly limited by the space in the room and especially by the absence of the ice surface. The challenge in these conditions is how to simulate the figure skating jump.
The figure skating jump landing can be simulated in the laboratory by stepping off a box (Dufek & Bates 1990; Foti 1990; Dufek & Bates, 1991; Charles 2015). The simulated jumps in the laboratory usually do not have the same number of vertical axis rotations as the regular jumps on the ice and also miss the horizontal motion during the jump take-off. During the regular on ice jumps, the skater lands on the front part of the blade where the toe picks are and then they shift their weight to the second third of the blade, because of the backward glide after the landing (Kho 1998). The ankle of the landing leg during the initial impact is partially plantar flexed, also due to the higher heel of the figure skating boot. The free leg is straight and moves posteriorly while the ankle of the landing leg (supporting leg) moves to dorsiflexion and the knee of the landing leg bends (Saunders et al. 2014). Kho (1998) has reported that the ankle dorsiflexion was greater during the jumps on the ice than during the laboratory simulations although the magnitude of the joint reaction forces at the knee and ankle were similar during both conditions indicating that also the GRF was similar during the laboratory simulation and on ice jumps.

However, different studies have presented different results regarding the impact force magnitude. Charles (2015) presented a force range of 5 to 8 times body during the landing impact, when measured during on ice performances via a special device containing strain gages that was attached directly on the blade of the skate. On the other hand, the skaters in Foti’s (1990) research experienced a peak vertical GRF of 4.12 ± 0.67 times body weight, when simulating figure skating jumps in a biomechanical laboratory. Here drop landings from a 30 cm raised platform were analyzed by video cameras and via force plate covered with an artificial ice surface. However, Kho (1998) highlighted that the heights were not representative of the jump height attained by figure skaters in previous on ice studies. For example King, Arnold & Smith (1994) who measured the heights of the jumps on ice have reported an average height of single axel 0.68 m, double axel 0.65 m and triple axel 0.66 m. As well as King, Arnold & Smith (1994), amongst others, have noticed the same constant heights across the single, double, and triple jumps (Lockwood and Gervais 1997).

A combination of both approaches, the laboratory and on ice measurements, was performed by Kho & Bishop (1998). The height obtained during the on ice jumps, was used to define the height of the box from which they stepped off for simulated landings in the laboratory. Kho (1998) reported that the decisive supporting factor during the landing impact is the knee extensor, which must absorb a much higher force when compared to the ankle muscles. This force redistribution may be explained by the support of the stiff skating boot
that reduces the demands of the ankle musculature to support the landing impact loads (Kho 1998).

Researchers have also studied the influence of the number of revolutions in the air on resultant GRF and position of body segments during the landing. Lockwood and Gervais (1997) found a relation between the number of rotations in the air and VGRF variables although the height of the jumps was comparable. They also observed time differences between the peak force of the forefoot and rearfoot sections and concluded that the time which is needed to distribute the force decreases with an increasing number of vertical revolutions in the air. To obtain this data they used the Micro EMED Insole System, which was placed inside of the figure skating boot of the landing foot. In contrast, Kho (1998) has not noted any differences in the magnitude of GRF between the single and double jump landings. Additionally, Kho (1998) did not report any differences in the ankle dorsiflexion and knee flexion angles which is in disagreement with the research of Lockwood, Baudin & Gervais (1996), who observed increased hip and knee flexion with a higher number of rotations in the jump while ankle flexion decreased. The differences between the studies may be due to different boot stiffness, which acts as a barrier that usually allows only minimal range of the motion at the ankle, as well as due to the different examination methods, different jumps, different skaters and different skates.

High VGRF during the landing impacts are affected by many factors, such as the landing surface (quality of the ice), angular position of individual body segments and the skating equipment (design, material and structure of the figure skating boot, as well as of the blade) (Dufek & Bates 1991). Ultimately many researchers concluded that changing the figure skating boot design can reduce the high injury rate among skaters of all figure skating disciplines (Lockwood, Baudin & Gervais 1996; Kho 1998; Kho & Bishop 1998; Dubravcic-Simunjak et al. 2003; Fortin & Roberts 2003; Bradley 2006; Bruening & Richards 2006; Haguenuer, Legreneur & Monteil 2006; Porter et al. 2007; Saunders et al. 2014; Campanelli et al. 2015).

1.6 Purpose, research question and hypothesis

If the frequency of jumping, and thus the exposure to landing impact forces, is very high it is advisable to find a way to decrease the landing impact forces and also decrease the risk of injury (Bressel & Cronin 2005; Ortega, Rodriguez Bies & Berral De La Rosa 2010). Skating
boot designs, constructions and outsole materials might affect the landing biomechanics. Therefore, understanding the landing biomechanics related to different skating boots may contribute to improvement of the current designs and to injury prevention (Cong 2012). The current study is thus focused on finding any differences in VGRF variables as well as differences in the landing angular positions of the lower extremity, hip and trunk during the landing impact between two different figure skating boots.

The purpose of this research is to obtain objective evidence, to accept or reject the following hypotheses: (1) Different figure skating boots (Graf Edmonton and Edea Concerto) differently affect the VGRF variables and kinematics during the landing impact. (2) Some figure skating boots (Graf Edmonton and Edea Concerto) may reduce the impact force at landing and could therefore possibly prevent injuries.

**Research questions:**

1. What is the material and construction of individually researched figure skating boots?
2. Are there any differences in VGRF variables during the landing impact between the researched figure skating boots?
3. Are there any differences in kinematics of the lower extremity, hip and trunk during landing impact between the researched figure skating boots?
2. Methods

There are several different brands and models of figure skating boots available, however due to the acquisition cost and the limited budget for the current study, only one pair of boots from two different brands were selected. The figure skating boots examined in this study were the Graf Edmonton special classic and Edea Concerto (figure 2). These boots were chosen on the basis of their popularity and availability in Sweden. The specific models were selected as the second hardest (stiffest) boot models offered from each brand. All subjects performed landings in both of these skating boots.


Figure skating blades are also produced by different companies and they differ from each other to varying degrees. On both types of boots will be mounted the exact same blades of the same size (Jackson ultima Matrix Supreme- light blade, figure 2), because different blades may affect any possible differences. These blades were selected because of the good accessibility. All subjects wore the same kind of nylon socks. Both the skates and blades selected for this research are commonly used by skaters worldwide, including skaters at the World Championships and Olympics.

The landing biomechanics in both skating boots were analyzed and compared. The biomechanical analysis was restricted to the landing phase and no data were collected during the take-off or air phase. The research was conducted in the Biomechanics and Motor Control (BMC) laboratory at The Swedish School of Sport and Health Sciences (GIH) in Stockholm, Sweden. The following methods were used for the examination of the landing biomechanics: in-shoe force and pressure measuring system (Pedar-X, Novel GmbH, Munich,
Germany), force plate (Kistler type 9281EA, Kistler AG, Winterthur, Switzerland) and motion capture camera system (Oqus 4, Qualisys AB, Gothenburg, Sweden).

**2.1 Research procedure and data collection**

The research procedure consisted of the following steps:
(1) Analysis of skating boots, (2) Selection of suitable subjects, (3) Determination of an appropriate jump landing simulation in the laboratory setting, (4) Planning of material, support and supervision during the laboratory measurement, (5) Laboratory measurement and experimental procedure, (6) Analysis of data and statistical comparison of the resulting data between examined boots, (7) Answers on the research questions and resulting conclusions.

**2.1.1 Analysis of skating boots**

The latest model was used for both types of boots. As the boots were brand new, it was necessary to “break them in” before the laboratory measurements. Therefore, one week before the measurements both skates were used on the ice for the same number of hours (each skate for 7 hours). This ensured that the skates were slightly softened and adapted better to the shape of the foot and therefore more realistically reflected the condition of the boots during in-season usage.

Information concerning the boot construction, technical parameters and materials used were initially requested from the manufacturers. In addition to this, old used boots of the same model were cut in half and analyzed by commonly available tools such as micro weight and calipers.

To examine stiffness differences among the boots, a bendability test was executed before the mounting of the blades. A skater performed a lunge test in a skating boot to assess the maximal dorsiflexion range of motion (assessed by measuring the distance between the front of the skate and the wall, at maximum knee/ankle flexion in the skating boot until the knee could still touch the wall). With consideration of the fact that the stiffness of the boot is also affected by the lacing technique, the skater was instructed to tie the shoelaces with the same tension (Campanelli et al. 2015). Instructions were given during to keep the heel permanently in contact with the ground. The bendability test will therefore be expressed in centimeters (The less centimeters measured during the bendability test the grater limitation of ankle flexion in the boot so the boot is more stiff).
The description of the boot included the following information: (1) Manufacturer, (2) Size of the boot, (3) Weight of the boot, (4) Thickness of the padding of the boot body, (5) Thickness of the tongue padding, (6) Cut of the boot (straight, angled, scalloped), (7) Lace fixation (eg, eyelets, hooks), (8) Sizes and proportions of the outsole, (9) The material used for the individual parts of the boot, (10) Stiffness.

2.1.2 Subjects and ethical aspects
As differences have been observed between subjects with different levels of experience as well as between females and males, the choice of subjects for this research was carried out with the intention of creating a homogeneous group of male advanced skaters, whose technique and skills are stable so the landing performed by individual subjects is as standardized as possible between attempts and differences seen are due to differences between the boots (Decker et al. 2003; Salci et al. 2004; Hou et al. 2005; Schmitz et al. 2007; Norcross et al. 2013). Also due to their experience, no learning effects are expected to confound the data collection. Another condition was that boot size 7 (UK men's size) fitted all subjects. Thirteen present or former advanced figure skaters (either single or pair), who lived in Stockholm, were contacted and asked to participate. Of these potential subjects, ten fulfilled the inclusion criteria.

All ethical aspects were according to Vetenskapsrådets (2002) demands. The subjects were informed about the research procedure, the risks involved, that all data would be treated anonymously and they were given ample time to decide if they wanted to participate or not. They were also informed that they could withdraw from this research at any time throughout the study. Because all subjects were older than fifteen years, there wasn't a need of guardian signature.

The final number of subjects was eight (age 31 ± 13 years, mass: 70 ± 12 kg, height: 180 ± 12 cm, years of competitive skating 14 ± 5 years). These subjects individually preferred and used different brands of boots (one participant used Jackson boots, one used Edea boots, two used Risport boots and four used Graf boots). At the time of data collection four of the subjects were current national level skaters and the rest were former national level skaters who worked as figure skating coaches in Stockholm. All subjects were in contact with ice on most days. They also all preferentially rotated in the counterclockwise direction in the air (landings on the right leg).
2.1.3. Jump landing simulation

Due to the limitations of examining landings from a regular figure skating jump on the ice, drop landings from boxes of two different, predefined, heights were performed as a simulation of on ice jump landings in the laboratory. The distance between the box and the force platform was determined by each subject individually for each box height, but the same conditions were used for both types of boot (see table 1 for the distances).

The participants performed a half vertical rotation in the air together with horizontal motion before they landed on the force platform on their preferred landing leg. The drop landings were performed from first a 30 cm and then a 50 cm box.

It is common to examine landing impacts by having subjects step off a box of predefined height instead of completing a regular jump, although the mechanics of drop landings differ from regular jump landings. For realistic laboratory landing simulations the principles of on ice landings have to be taken into account, i.e. that the landing was preceded by vertical axis rotation and horizontal motion. Furthermore, during the landing, skaters glided away from the place of the IC while shifting their weight from the front part of the blade to the second third of the blade. Artificial ice panels were placed in the floor of the laboratory in order to try to mimic the conditions on ice and allow the blade to glide during landing (figure 3).

Each subject was instructed to stand with the left foot at the edge of the box and with the right foot extended backwards (as in preparation for an axel jump). Instructions were: while facing the force platform,

<table>
<thead>
<tr>
<th></th>
<th>30 cm box</th>
<th>50 cm box</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Subject 1</strong></td>
<td>93 cm</td>
<td>99 cm</td>
</tr>
<tr>
<td><strong>Subject 2</strong></td>
<td>88 cm</td>
<td></td>
</tr>
<tr>
<td><strong>Subject 3</strong></td>
<td>80 cm</td>
<td>80 cm</td>
</tr>
<tr>
<td><strong>Subject 5</strong></td>
<td>70 cm</td>
<td>73 cm</td>
</tr>
<tr>
<td><strong>Subject 6</strong></td>
<td>83 cm</td>
<td>83 cm</td>
</tr>
<tr>
<td><strong>Subject 8</strong></td>
<td>100 cm</td>
<td>100 cm</td>
</tr>
</tbody>
</table>

Table 1. Individual distance between box and force plate.

Figure 3. Artificial ice surface in the laboratory.
reach straight out with the dominant leg like entering the waltz jump or axel, perform half a vertical revolution in the air and shift your weight from the supporting leg onto the landing leg. The movement of the upper extremities should be the same as when performing a waltz jump or axel on the ice. The execution of landing should be the same as from a regular jump on the ice (landing only on one leg, in this case on the right landing leg). During the landing the motion in the knee should be as large as possible. The landing phase finished when the knee returned to the straightened position.

Each subject was instructed not to jump vertically upwards or outwards from the box and not to lower the body center of mass before entering the jump to maintain the same initial height for all landings. Each subject practiced the jump landing simulations within the warm up until they felt comfortable with the task.

2.1.4 Experimental procedure

Prior to the measurements, all subjects were asked to warm-up as they wished and to practice a series of jump simulations from the boxes of both heights. During the measurements, all subjects performed landings from 30 cm and 50 cm boxes and with both boot models. Kinematic and VGRF parameters were examined during all landings using in-shoe force and pressure measuring (Pedar-X, Novel GmbH, Munich, Germany), force plates (Kistler type 9281EA, Kistler AG, Winterthur, Switzerland) and motion capture analysis containing 12 video cameras (Oqus 4, Qualisys AB, Gothenburg, Sweden). These systems were synchronized using the novel wireless unit (Pedar-X, Novel GmbH, Munich, Germany).

Kinematic examination focused on the lower landing limb (right ankle, knee and hip), and trunk during the landing. The VGRF and plantar pressure examination focused only on the landing foot (right). For the purpose of this research, the following variables were analyzed and compared between the two types of figure skating boots. These variables were chosen based on former studies and figure skating research (Haguenauer, Legreneur & Monteil 2006; Bruening & Richards 2006; Lockwood & Gervais 1997; Goonetilleke 2012; Puddle & Maulder 2013; Ramanathan et al. 2010).

VGRF and pressure variables:

All force variables were examined by both the Kistler force plate system and Pedar-X system.

- Maximum impact force (N), (The highest force experienced by the foot upon impact)
- Force time integral (N*s), (The area under the max force-time curve)
• Time to maximal force (s), (The time from IC to maximal vertical force)

All pressure variables were only examined by the Pedar-X system.
• Maximum impact pressure (Pa), (The highest pressure experienced by the foot upon impact)
• Pressure time integral (Pa*s), (The area under the max pressure-time curve)
• Time to maximal pressure (s), (The time from IC to maximal vertical pressure)
• Center of pressure (The location of center of pressure at the IC and its shift prior the landing stabilization)

For the Pedar-X force and pressure examination the foot was also divided into separate foot sections: forefoot, midfoot and rearfoot.

Kinematic variables:
• Ankle at initial ground contact (°), (Ankle plantarflexion at IC)
• Knee at initial ground contact (°), (Knee flexion at IC)
• Hip at initial ground contact (°), (Hip flexion at IC)
• Trunk at initial ground contact (°), (Trunk flexion at IC)
• 1\textsuperscript{st} peak ankle flexion (°), (Maximal ankle dorsiflexion after IC)
• Time to 1\textsuperscript{st} peak ankle flexion (°), (The time from IC to 1\textsuperscript{st} peak ankle dorsiflexion)
• 1\textsuperscript{st} peak knee flexion (°), (Maximal knee flexion after IC)
• Time to 1\textsuperscript{st} peak knee flexion (°), (The time from IC to 1\textsuperscript{st} peak knee flexion)
• 1\textsuperscript{st} peak hip flexion (°), (Maximal hip flexion after IC)
• Time to 1\textsuperscript{st} peak hip flexion (°), (The time from IC to 1\textsuperscript{st} peak hip flexion)
• 1\textsuperscript{st} peak trunk flexion (°), (Maximal hip flexion after IC)
• Time to 1\textsuperscript{st} peak trunk flexion (°), (The time from IC to 1\textsuperscript{st} peak trunk flexion)

Half of the participants were randomly allocated to start with Edea boots and the other half with Graf boots. Participants were asked to tie the laces of both skates with the same tension.

Each subject completed 6 successful testing trials of each task with up to 30 seconds of rest between trials to minimize the potential effects of fatigue. Trials were deemed successful if the subjects landed on the force platform and, as would happen on the ice, glided away from the IC place without losing their balance or making a technical fault. Furthermore,
it was monitored that participants used minimal horizontal motion and did not lower the body center of mass before entering the jump. After the completion of all tasks with the first pair of boots the participant had a few minutes to rest and to prepare for the next set of trials with the other pair of boots.

2.1.4.1 Specification of measuring systems

2.1.4.1.1 Pedar X

Pedar-X in-shoe force and pressure measuring system (Pedar-X, Novel GmbH, Munich, Germany) was used to assess the plantar pressure and force which acts between the foot and the skate. Such information is important for the evaluation of the skating boot design, biomechanics of landing, and injury prevention. The Pedar-X insole, which was placed only in the right boot, was connected to Pedar-X box and battery, which were, together with the Novel wireless unit, attached to the skater’s hip by a purpose made belt. The entire system weighed a little over 360 g (including the Pedar-X box, battery and novel wireless unit) and the thickness of the insole was 1.9 mm. A great advantage of this system, which contains 99 embedded sensors, is its mobility and wireless transmission to a computer via Bluetooth (Ramanathan et al. 2010). A sampling rate of 200 Hz was used, this frequency was recommended for the accurate measurement of plantar pressures while jogging (Urry 1999).

The accuracy and reliability of the Pedar-X system was tested in by Barnett, Cunningham & West (2001) and has correlated well with results obtained using a Kistler force platform. Also Ramanathan et al. (2010) concluded high and moderate degree of repeatability and accuracy of Pedar-X, which therefore can be used as a valuable tool in the assessment of insole plantar pressure and force distribution. Furthermore, the force and pressure recorded by the Pedar-X system appeared to be influenced by the different type of shoes worn (Barnett, Cunningham & West 2001). Therefore data obtained by the Pedar-X system can detect differences in the forces and pressures at the foot with different type of figure skating boots.

The preparation procedures of Pedar-X system proceeded as directed in the manufacturer’s manual. The insoles were calibrated by the manufacturer and before data acquisition, the zero setting procedure was performed as recommended by Novel.
2.1.4.1.2 Kistler force plate

A force plate (Kistler type 9281EA, Kistler AG, Winterthur, Switzerland) was used to assess the force which acts between the artificial ice and the ground underneath the ice. The ice section on the force plate was cut so no forces were dissipated to any surface outside the force plate. The system sampled data at a frequency of 2500 Hz. The advantages of a force plate system compared to in-shoe measuring system are higher precision, higher operating frequency, and greater measuring range (Barnett, Cunningham & West 2001; Abdul Razak et al. 2012). As the force plate is firmly attached to the ground, the pressure sensors are always positioned parallel to the surface and therefore it provides a “true” vertical and horizontal force measurement.

2.1.4.1.3 Qualisys motion capture system

To assess the kinematics of the landing trials, these were recorded by a motion capture system containing 12 video cameras (Oqus 4, Qualisys AB, Gothenburg, Sweden) at a sampling frequency of 250 Hz.

Before recording, 66 passive markers were placed on the boots and on the subjects’ anatomical landmarks to track the 3D motion of the trunk, pelvis and lower limbs. On the skating boot, markers were located at the lateral and medial malleolus, at the head of first and fifth metatarsals, and also on the front and rear side of the skate (the location of anatomical landmarks in the skating boot were found with the help of calipers). Lower limb markers were placed on the medial and lateral aspects of the knee, anterior superior iliac spine, greater trochanter and on the posterior superior iliac spine. Trunk markers were placed on the sternum xiphisternal joint and on the cervical vertebrae 7. Upper limbs markers were placed on the acromioclavicular joint, lateral and medial epicondyle of humerus, radius-styloid process and ulna-styloid process and on the lateral and medial head of metacarpal. A cluster of four markers was placed on the front shank and thigh, and cluster of three markers was placed on lateral arm and forearm.

2.1.5 Data Analysis

Due to technical problems with the Pedar-X insoles only data from six of the eight subject s were analyzed. One of these subjects completed the trials only from the smaller box (30 cm).
Kinematic data were first processed in Qualisys Track Manager (QTM) software, where all passive markers, which were placed on the subjects’ bodies, were tracked and named individually for each subject and each trial. For further analysis, all data files were exported from QTM to the Visual3D v5 Professional software. In Visual3D a model was created of a human body for each subject using each type of boot, this was then applied to all trials for that particular person. All data were normalized to body weight and height of each subject, but the mass of the skates was neglected. A low pass Butterworth filter with a cutoff frequency 7 Hz was applied to all kinematic data. The individual joint angles at IC, peak flexion and time to peak were calculated in Visual 3D. After visual inspection of all trials of each participant and after some corrections to the peak flexion angle values (to select the first peak value after the initial contact, not the maximum value) all values were exported to Excel. Additionally, maximal VGRF values from the Kistler force plate were exported to Excel from the Visual3D software. Time to maximal force and force time integral were not exported due to technical limitations.

Pedar data were first exported from the Pedar online software to Spike2 software for analysis. On a force-time curve of each trial and each foot section (forefoot, midfoot and rearfoot) as well as for the whole foot the position of IC (by one vertical cursor which was set on the beginning of the slope) and maximum value (by another vertical cursor which was set on the max peak value) were set. With this setting the software calculated the values for peak impact force, force time integral (the area under the max force-time curve) and time to peak. All values were then exported to Excel.

In Excel, tables were created for each participant with six values from the six trials assigned to each variable for each boot. The next step was deletion of the highest and lowest values for each variable from the six trials (to make the average from as consistent values as possible, which may increase the reliability of measured data) and the remaining values were averaged.

To statistically prove any differences between the Graf boot and Edea boot, average values of all subject s were compared between the boots in IBM SPSS Statistics software. According to the result of the Shapiro-Wilk test, either paired samples T-test or non-parametric two-related-samples test (Wilcoxon test type) were used. Statistical significance level of p≤0.05 was set throughout.
3. Results

3.1 Results from the analysis of skating boots

Table 2 presents the differences between the boots. See figure 4 for illustration of the values in the table (this figure was taken from the Pixabay website and was adjusted for explanation purposes). See also figure 18 in appendix 2 for individual parts of figure skating boot and figure 19 of a boot cut in half.

Figure 4. Illustrative picture of the figure skating boot.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>GRAF (Edmonton)</th>
<th>EDEA (Concerto)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Size of the boot</strong></td>
<td>7 (UK men's size)</td>
<td>7 (UK men's size)</td>
</tr>
<tr>
<td><strong>Weight of the boot</strong></td>
<td>795 g (one boot)</td>
<td>760 g (one boot)</td>
</tr>
<tr>
<td><strong>1. Thickness of the padding of the boot body</strong></td>
<td>a) 1,3 cm</td>
<td>a) 1,5 cm</td>
</tr>
<tr>
<td></td>
<td>b) 1,2 cm</td>
<td>b) 1,3 cm</td>
</tr>
<tr>
<td></td>
<td>c) 0,6 cm</td>
<td>c) 0,8 cm</td>
</tr>
<tr>
<td><strong>2. Thickness of tongue padding</strong></td>
<td>1,1 cm</td>
<td>1,9 cm</td>
</tr>
<tr>
<td><strong>3. Cut of the boot</strong></td>
<td>Straight</td>
<td>Angled</td>
</tr>
<tr>
<td><strong>4. Lace fixation</strong></td>
<td>4 hooks</td>
<td>3 hooks</td>
</tr>
<tr>
<td><strong>5. Sizes and proportion of the outsole</strong></td>
<td>d) outsole height 1 cm</td>
<td>d) outsole height 1,5 cm</td>
</tr>
<tr>
<td></td>
<td>e) height of heel 4,6 cm</td>
<td>e) height of heel 6,2 cm</td>
</tr>
<tr>
<td></td>
<td>f) outsole width 9,5 cm</td>
<td>f) outsole width 8 cm</td>
</tr>
<tr>
<td></td>
<td>g) width of heel 5,1 cm</td>
<td>g) width of heel 5,1 cm</td>
</tr>
<tr>
<td></td>
<td>h) length of heel 6 cm</td>
<td>h) length of heel 5,6 cm</td>
</tr>
</tbody>
</table>

**The material used for the individual parts of the boot**

(Only materials that have been listed on the manufacturer's websites or which the manufacturer informed about. There are probably also other materials used in the skating boot)

**Outsole**-leather midsole with tapered edge profile, self-reinforcing polypropylene (SRPP) surface, beechwood heel, shock-absorbing rubber

**Boot body**-leather, laminated fabric, microfiber, soft foam and metal hooks

**Bendability test** (average of five trials in the left and right boot)

| | 7,65 cm (more stiff boot) | 12,25 cm (less stiff boot) |
Differences between the boots are more or less evident in each category of the table. The different heights of the heels, proportion of the outsoles and stiffness of the boots influence the body alignment. This is also evident in the different angular position of the lower limb segments which are presented in the kinematic results below.

3.2 Kinematic and VGRF results

In the following sub sections figures are presented in which the average values of each subject between Graf Edmonton and Edea Concerto boot are compared.

3.3 Statistically significant differences in VGRF

Only statistically significant variables are presented in the following figures. For the Pedar-X force examination the foot was divided into separate foot sections: forefoot, midfoot and rearfoot (figure 5). See figure 6 of force-time curve for an illustration of the force variables.

Statistically significant differences in VGRF variables between the Graf Edmonton and the Edea Concerto were only seen from the Pedar-X measuring system in the maximal impact force from 30 cm and 50 cm box heights (for the whole foot and the rearfoot section) and for the area under the maximal force-time curve from the higher box (for the rearfoot section only).

Other figures of variables such as maximal force from the force plate and for the Pedar-X forefoot and midfoot sections as well as the area under the maximal force-time curve (Pedar-X whole foot, forefoot and midfoot sections) and time to maximal force where no statistically significant differences were seen between the boots are presented in appendix 2. Also average values of all participants for the maximal force, time to maximal force and the area under the maximal force-time curve are presented in appendix 2.
Figure 6. Force-time curve, illustrating the variables investigated in this study.

Figure 7 (a): Pedar- max force (whole foot 30 cm BOX), 6 (b): Pedar- max force (whole foot 50 cm BOX), 6 (c): Pedar- max force (rearfoot section, 30 cm BOX) and 6 (d): Pedar- max force (rearfoot section, 50 cm BOX) the differences between the individual values of each subject are presented for the highest VGRF experienced by the foot during the landing impacts. The higher the force, the greater the demand on the body for force absorption. From the figure it is evident that for each subject a significantly greater force acted during the landing impacts in the Graf Edmonton boot compared with the Edea Concerto boot (level of significance p≤0.05). Also with increased height the maximal VGRF increased as well.
Figure 7. Significant differences in VGRF variables between the Graf Edmonton and Edea Concerto boots where each value for the subject represent the average of six trials.
Figure 8 Pedar- area under the max force-time curve (rearfoot section, 50 cm BOX) the differences between the individual values of each participant are presented for the force-time integral. From the figure it is evident that for each participant a significantly greater area under the maximal force-time curve acted during the landing impacts in Graf Edmonton boots compared with the Edea Concerto boot (level of significance p≤0.05).

<table>
<thead>
<tr>
<th>Force plate</th>
<th>Participant 1</th>
<th>Participant 3</th>
<th>Participant 5</th>
<th>Participant 6</th>
<th>Participant 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pedar</td>
<td>GRAF</td>
<td>EDEA</td>
<td>GRAF</td>
<td>EDEA</td>
<td>GRAF</td>
</tr>
<tr>
<td>Max force (N)</td>
<td>2795.600</td>
<td>3733.590</td>
<td>3876.676</td>
<td>3528.868</td>
<td>838.008</td>
</tr>
<tr>
<td>Pedar (whole foot)</td>
<td>*1604,220</td>
<td>*2014,884</td>
<td>*38,766</td>
<td>*35,288</td>
<td>0,057</td>
</tr>
<tr>
<td>Pedar (forefoot)</td>
<td>712,052</td>
<td>824,869</td>
<td>31,417</td>
<td>29,858</td>
<td>0,062</td>
</tr>
<tr>
<td>Pedar (midfoot)</td>
<td>111,292</td>
<td>137,605</td>
<td>2,598</td>
<td>2,161</td>
<td>0,051</td>
</tr>
<tr>
<td>Pedar (rearfoot)</td>
<td>*838,008</td>
<td>*1128,706</td>
<td>18,682</td>
<td>*4,927</td>
<td>0,065</td>
</tr>
<tr>
<td>Pedar (midfoot)</td>
<td>84,731</td>
<td>99,015</td>
<td>1,583</td>
<td>1,443</td>
<td>0,045</td>
</tr>
</tbody>
</table>

In table 3 is presented a brief overview of average values of all subjects for particular force variables from two different box heights (box 1- 30 cm, box 2- 50 cm). The values for which significant difference was found (level of significance p≤0.05) between the skates are marked with * and are highlighted in green.

Table 3. An overview of the average values of all subjects for all particular force variables.
3.4 Statistically significant differences in kinematics

Only statistically significant variables are presented the following figures. Statistically significant kinematic differences between the Graf Edmonton and the Edea Concerto boots were seen in the ankle IC flexion from the 50 cm high box, 1\textsuperscript{st} peak ankle flexion angle from 30 cm and 50 cm box heights and for the knee IC flexion from the 50 cm high box. Figures illustrating variables with non-significant differences between variables are presented in appendix 2. Figure 9 illustrates joint angle conventions created for representation of the specific joint angles presented in the figures.

Figure 10 (a) presents knee flexion at IC (50 cm box). The differences of individual values of each subject are presented for knee flexion at the IC from the 50 cm box. It is evident that the subjects had significantly greater flexion of the knee in the Graf Edmonton boot compared to the Edea Concerto boot (level of significance p≤0.05).

In Figure 9 (b, c, d) ankle flexion at IC (50 cm box), 1\textsuperscript{st} peak ankle flexion (30 cm box) and 1\textsuperscript{st} Peak ankle flexion (50 cm box) are presented for the ankle joint angle at the IC from the 50 cm high box as well as for the 1\textsuperscript{st} peak ankle joint flexion from the 30 cm and the 50 cm high box. The higher the number for IC and 1\textsuperscript{st} peak flexion the greater the dorsiflexion of the foot. It is evident that the subjects had significantly greater dorsiflexion of the foot in the Graf Edmonton boot compared to the Edea Concerto boot (level of significance p≤0.05). This may be due to the higher heel in the Edea boot. Also with the increased height the 1\textsuperscript{st} peak ankle flexion increased as well.
Figure 10. Significant differences in kinematic variables between the Graf Edmonton and Edea Concerto boots where each value for the subject represent the average of six trials.
In table 4 is presented a brief overview of the average values of all subjects for particular kinematic variables from two different box heights (box 1 - 30 cm, box 2 - 50 cm). The values for which significant difference was found (level of significance p≤0.05) between the skates are marked with * and are highlighted in green.

<table>
<thead>
<tr>
<th>Kinematic Variable</th>
<th>Box 1</th>
<th>Box 2</th>
<th>Box 1</th>
<th>Box 2</th>
<th>Box 1</th>
<th>Box 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>IC Flexion (in degrees)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ankle</td>
<td>Graf</td>
<td>*220,7919</td>
<td>*253,6580</td>
<td>*256,2570</td>
<td>0,1095</td>
<td>0,1100</td>
</tr>
<tr>
<td></td>
<td>Edea</td>
<td>*215,2374</td>
<td>*249,2152</td>
<td>*250,9631</td>
<td>0,1090</td>
<td>0,1136</td>
</tr>
<tr>
<td><strong>Peak Flexion (in degrees)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee</td>
<td>Graf</td>
<td>*207,2915</td>
<td>241,2670</td>
<td>246,5573</td>
<td>0,1453</td>
<td>0,1504</td>
</tr>
<tr>
<td></td>
<td>Edea</td>
<td>*204,4263</td>
<td>241,0900</td>
<td>245,6575</td>
<td>0,1533</td>
<td>0,1550</td>
</tr>
<tr>
<td><strong>Time to peak (in seconds)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip</td>
<td>Graf</td>
<td>205,8400</td>
<td>205,1037</td>
<td>247,4812</td>
<td>0,4302</td>
<td>0,4094</td>
</tr>
<tr>
<td></td>
<td>Edea</td>
<td>205,8395</td>
<td>204,4295</td>
<td>246,7345</td>
<td>0,4063</td>
<td>0,4646</td>
</tr>
<tr>
<td>Trunk</td>
<td>Graf</td>
<td>210,2842</td>
<td>210,5069</td>
<td>250,8085</td>
<td>0,3423</td>
<td>0,3526</td>
</tr>
<tr>
<td></td>
<td>Edea</td>
<td>210,6804</td>
<td>210,6878</td>
<td>250,8205</td>
<td>0,3563</td>
<td>0,3916</td>
</tr>
</tbody>
</table>
4. Discussion

A search of previous research on this topic revealed no work on the topic. So it is assumed that this work is the first of its kind. A comparison of the examined figure skating boots found differences between the two brands.

On the basis of previous studies and the results of this research factors were identified that may contribute to the development of injuries. This information may be useful for improving and designing new figure skating boots, such as the construction design and material selection, with emphasis on injury prevention because the future footwear alterations may lead to a decrease in vertical ground reaction force and a lower exposure of the body to the acting forces.

Finally, some authors of studies devoted to figure skating have mentioned a limitation of applying their results to the entire figure skating population, as the results may depend on the brand of figure skating boots which the researched participants have used (Campanelli et al. 2015). The current results clarify that the differences between the figure skating boots are significant.

The subjects experienced, during the landing impact in both boots, a load of high intensity and short duration while the range of motion of ankle and knee were limited by the boots. Only statistically significant variables are discussed here.

The degree of right ankle and knee joint flexion during the IC was different between the skating boots (during the landings from 50 cm high box) as was the degree of right ankle joint peak flexion (during the landings from 50 cm and 30 cm high boxes). Also the values for the force magnitude experienced by the right foot upon the landing impacts (for the whole foot and the rearfoot section measured by Pedar-X insole, from the 30 cm and 50 cm high boxes) and for the area under the max force-time curve (for the rearfoot section measured by Pedar-X insole, from the 50 cm high box) differed between the boots.

The subjects had greater plantar flexion of the foot and less knee flexion at IC and smaller peak dorsiflexion after the IC in the Edea boot compared to the Graf boot. Simultaneously lower values of force were observed in Edea boot compared to the Graf boot during the landing impacts. This may imply that greater plantar flexion of the foot at the IC allows the triceps surae muscle to decrease the velocity of descent and permit a more extended knee at IC to provide better gradual deceleration of body segments, resulting in lower forces experienced by the foot. This finding agrees with the findings of Bruening & Richards study (2006) and Rowley & Richards study (2015). The average additional force
(for the whole foot measured by Pedar-X insole) which the skater had to absorb with each landing in Graf Edmonton boot compared to Edea Concerto boot was 283,351 N (28,894 kg) during landings from the smaller box and 227,856 N (23,235 kg) from the higher box.

Due to the fact that a competitive figure skater in the singles discipline can land up to 100 jumps a day, this difference between the boots is important (Bruening & Richards 2006). Multiple daily repetitions of landing in boots in which the skater must absorb higher VGRF increases the risk of accumulation of micro-trauma and thereby increases the risk of overuse injuries (Nash 1988; Nigg & Bobbert 1990; Kho 1998; Zhang, Bates & Dufek 2000; Besier et al. 2003; Dubravcic-Simunjak et al. 2003; Fortin & Roberts 2003; Acuña et al. 2014; Saunders et al. 2014; Charles 2015). When comparing the landing biomechanics from the lower and higher box, a greater force was observed during the landing from the higher box while no significant difference was observed in the angular position of examined body segments.

The reason of greater plantar flexion of the foot at the IC and smaller peak dorsiflexion in Edea boots compared to Graf boots may be due to the different heights of the heels, size proportions of the outsoles and stiffness of the boots. Although the Graf Edmonton is stiffer and limits the range of ankle and knee motion more due to the stiffness, it gives better support to the feet and ankle while performing demanding jumps, spins and steps. For this reason (the higher stiffness of the boot) and also due to the smaller heel, the Graf boot may protect the foot better before the risk of ankle sprain (Cong 2012; Campanelli et al. 2015; Rowley & Richards 2015). On the other hand, Van Der Worp et al. (2014) suggested that the risk of injury increases with reduced range of motion of joint flexion angles and high joint angular velocities during a landing. It is assumed that in this case the stiffness of the boot can slow down the landing angular velocity of the ankle (Cordova et al. 2010). Higher stiffness of the boot can in turn relate to higher friction stresses and pressures on the foot which may result in the most common skating related problem, the bursitis (Bradley 2006).

The height of the heel is 1.1cm higher in the Edea Concerto compared to the Graf Edmonton. The different heel heights affect the foot and body alignment differently in terms of muscle activity, redistribution of plantar stresses and GRF (Cong 2012). Increased heel height in the Edea boot resulted in increased ankle plantar flexion which may cause the foot to slide forward along the inclined supporting surface and press the toes against the toe box which increases the mechanical stresses and friction pressure on the forefoot (Cong 2012).
Another difference between the boots was in the area under the maximal force-time curve (for the rearfoot section of Pedar-X insole). Without further analysis it is not possible to say with certainty whether the lower values, which were measured in the Edea are better or not, because it is necessary to also evaluate the shape of the curve, i.e. how steep is the ascent of the curve, how high is the peak and the time duration of the ascent of the curve until the peak. Due to time limitation, such analysis was not performed in the current study.

For the time to 1st peak flexion variable in kinematics and time to maximal force variable in VGRF no statistically significant differences were seen between the boots, suggesting that the force is dissipated over a similar period of time. Also for hip and trunk flexion angles no differences were detected between the boots.

Due to a number of recent changes in this sport, such as growth in popularity, increased number of participants, rapid progression in the technical elements, more hours spent in training of the jumping elements, and starting with serious practice at younger ages, the risk and number of overuse injuries among competitive figure skaters have increased. For this reason, the prevention of overuse injuries deserves more emphasis than ever. A continuation of this research and selection of suitable figure skating boots is therefore very important.

4.1 Limitations

4.1.1 Simulation of jumps in a laboratory setting

This study was conducted in a biomechanical laboratory and not in an ice rink, where the figure skating boots and jumps would actually have the most natural conditions for the research. There were several reasons for this choice. It was not possible to place the force plate beneath the ice surface in an ice rink and it was easier to create constant conditions for both analyzed skates and for all participants in the laboratory.

It must be taken into account that unlike the simulated jumps in the laboratory, the jumps on ice have different take-off velocities, angular momentum, technique and landing surface which most likely affects the stress responses (Acuña et al. 2014). It should also be noted that the force plate was placed under a piece of plastic ice. For this reason the measured values from the force plate were affected by the artificial ice lying on top of it. On the other hand it is important that the same conditions were maintained for both examined boots.
4.1.2 1st peak flexion in kinematic analysis

The reason why the 1st peak flexion was selected in kinematic examination instead of the maximal flexion is because sometimes the subjects have raised up from the 1st peak flexion after the IC and then went back to even greater flexion. It is considered that this second higher peak was not necessary for force absorption, but was a requirement for the correction of the landing technique.

4.1.3 Pressure data

The reason why the Pedar-X data for pressure values were not analyzed was the limited access to Pedar online software. Another reason is that for some participants up to four duplicate values have often appeared out of six for the maximum pressure values. Due to the impossibility to check these values in the original program, these values were evaluated as incorrect in 2D or 3D models.

4.1.4 Sampling frequencies

Each measuring system such as Kistler force plate, Pedar-X system and Qualisys motion capture system have sampled under different frequencies. The Kistler system sampled at the frequency of 2500 Hz, Qualisys motion capture system at 250 Hz and Pedar-X system at 200 Hz. Despite the fact that the force data received from Pedar-X system looked good the question is whether the 200 Hz frequency is sufficient to measure and analyze jump landings.

4.1.5 Boots and blades

Due to financial limitation only two different brands/models of figure skating boots were compared. Specific brands were selected according to their popularity among the competitors in Sweden. The specific models of boots, Concerto from Edea and Edmonton from Graf, were selected as the second hardest (stiffest) boot models offered from each brand. It must be mentioned, that during the research period the Edea company began to offer a new model of a boot, which shifts Edea Concerto to third place in terms of the offered boot hardness (stiffness).

From each brand only one pair of boots of the same size was provided. It is possible that even among the boots of same brand and same size there may be small
differences, for example in the weight. In the future it would be advisable to examine the differences between the brands with several pairs of same size boots from each brand.

A pair of same blades was provided for each pair of boots. The specific brand of blades was selected because of their good accessibility.

4.1.6 Subjects

The choice of subjects for this research was based upon creating a homogeneous group of advanced skaters, whose technique and skills are stable, so the landing performed by individual subjects would be as close to being identical on each attempt as possible and will not affect the differences between the boots. Furthermore, only skaters who lived in Stockholm were asked to participate in the research. Due to financial limitations it was not possible to ensure the participation of skaters from other parts of Sweden.

The original plan was to measure the differences between the boots at the landing impact of triple jumps but, due to the complexity of these jumps and the small number of women living in Stockholm who could land these jumps, only male advanced figure skaters were contacted. Finally, due to financial limitations only one pair of boots from each tested brand was provided, so another condition for the participation in this research was to fit the skates of size 7 (UK men's size). Given all these constraints, there were a very limited number of potential subjects for this research.

4.1.7 Error of Pedar-X insole

During the measurements, only one Pedar-X insole was used and was inserted into the right boot. This insole was moved from one boot to the other as required for measurements. In the second half of the measurement for the sixth subject, an error message started to show up from several sensors of the insole. For this reason, the research was prematurely terminated and the last two subjects did not take part in the measurements. The assumed cause of these errors was a very tight pressure on the lateral aspect of the stiff skating boot which compressed the sensor electronics.

Another limitation of the measurements with Pedar-X insole system was that due to the position of the insole within the shoe relative to ground, the insole can measure only the 'normal' force, not the 'true' force (the true vertical force can only be measured with a system that is rigidly fixed to the supporting surface) (Orlin & Mcpoil 2000).
4.1.8 Human body models for kinematics analysis

In the human body models for individual skaters in Visual3D, the mass of the skates was not incorporated. The weight difference between the examined skates is 35 grams.

4.1.9 Time to peak variables from force plate data

When TTP from force plate data was evaluated in Visual3D software, it was not possible to precisely mark the exact time for the maximum peak force. This was probably due to the very high and short peak duration with very steep slope and rapid descent. Due to the distortion of such data, they were not further evaluated.

4.2 Future research

It would be good to continue with this research in the future, to include different brands and more boot pairs of different boot sizes. Also it is important to include women and compare any differences between the boots and gender. Separate research should focus on examining and comparing various figure skating blades. The research should focus not only on the differences between the boots and blades at the landing impact but also on the differences during the take-off. Moreover, an examination of muscle activity by electromyography (EMG) to find out whether the different stiffness of the boot affects the calf muscle activity would be appropriate.
5. Conclusions

The outcomes indicated significant differences between the examined boots in exposure of the body to the VGRF and in angular position and flexion range of the ankle and knee during the landing impact suggesting that footwear plays an important role in these aspects. Both hypotheses were accepted, indicating that different figure skating boots differently affected the VGRF variables as well as the kinematics during the landing impact and some figure skating boots may reduce the impact at landing more than others and therefore could possibly prevent injuries.

It cannot be concluded which of the examined figure skating boots were more gentle to the human body, because each boot had its pros and cons, but also because differences between the boots during the take-off and during skating itself were not examined. However, the Graf boot was stiffer and has more limited range of ankle and knee motion. Due to this stiffness better support can be given to the feet and ankle while performing demanding jumps, spins and steps. For this reason and also due to the smaller heel, when compared with Edea boot, the Graf boot may protect the foot better before the risk of ankle sprain. On the other hand, considering the fact that the subjects were exposed to higher VGRF during the landing in Graf boots, which is one of the crucial factors that contributes to the development of overuse injuries, the Edea boots were more gentle to the human body during the landing impacts.
References


• Campanelli, V., Piscitelli, F., Verardi, L., Maillard, P. & Sbarbati, A. (2015). Lower Extremity Overuse Conditions Affecting Figure Skaters During Daily Training. *Orthopaedic journal of sports medicine*, 3(7), ss. 1-12


• Kho, M. E. (1998). *Bone-on-bone Forces at the Ankle and Knee in Figure Skaters During Loop Jumps: Clinical Implications*, University of Waterloo.


• Orendurff, M. S., Rohr, E. S., Segal, A. D., Medley, J. W., Green, J. R., 3rd & Kadel, N. J. (2008). Regional foot pressure during running, cutting, jumping, and landing. The American journal of sports medicine, 36(3), ss. 566-571.


• Shulman, C. (2002). *The Complete Book of Figure Skating*. Champaign, IL, United Kingdom: Human Kinetics.


Appendix 1.

Literature research

The purpose of this research is to obtain objective evidence accept or reject the following hypotheses: (1) Different figure skating boots differently affect the VGRF variables and kinematics during the landing impact. (2) Some figure skating boots may reduce the impact at landing and could therefore possibly prevent injuries.

Research questions:

1. What is the material and construction of individually researched figure skating boots?
2. Are there any differences in VGRF variables during the landing impact between the researched figure skating boots?
3. Are there any differences in kinematics of the lower extremity, hip and trunk during landing impact between the researched figure skating boots?

Keywords for research

| Figure skating, boots, figure skating boots, injuries, knee, back, ankle, skaters, ice, jump, jumps, ground reaction force, pedar insole, skaters, GRF, VGRF, kinematics, figure skater, skates, blades, biomechanics, history, force plate, drop jump, countermovement jump |

Where have you searched?

| Sport discus, Google Scholar, Pubmed |

Searches that returned relevant results

| Sport discus: Figure skating injuries, history, back, ankle, knee, jumps |
| Pubmed: GRF, VRGF, Ground reaction force, kinematics, biomechanics, figure skating, injuries, skates |

Comments
Appendix 2.

In part I. and part II. sub sections figures are presented, in which the values between Graf Edmonton and Edea Concerto boot, from two different box heights (box 1-30 cm, box 2-50 cm) are compared. Each value for the box 1 is the average value for a particular variable of six participants and all their trials. Each value for box 2 is the average value for a particular variable of five participants and all their trials (each participant except one completed 6 trials from each height with each boot). In part III. Sub section are presented figures of individual parts of figure skating boot and of a boot cut in half.

Part 1. Kinematics

The results from kinematic analysis of jump landings in two different figure skating boots are presented in the following figures. Variables which are compared in the figures are flexion at initial ground contact (I.C. flexion), 1st peak flexion and time to 1st peak flexion (TTP). Values for I.C. flexion and for 1st peak flexion are angles presented in degrees. Figure 9 illustrates joint angle conventions created for representation of the specific joint angles presented in the figures. TTP represents the time between the I.C. flexion and the 1st Peak flexion.

In figure 11 ankle flexion the values for ankle joint angle are presented. The higher the number for I.C. flexion and 1st Peak flexion the greater the dorsiflexion of the foot. Lower value for TTP indicates a faster shift into the 1st peak flexion of the ankle joint. With the increased height the average TTP increased as well.

Figure 9. Joint angles presented in the kinematic figures.
In figure 12 knee flexion the values for the knee joint angle are presented. A higher number for I.C. flexion and 1st peak flexion represents a greater range of motion in the knee joint. A lower value for TTP indicates a faster shift into the 1st peak flexion of the knee joint. With the increased height the average TTP increased as well.
In figure 13 hip flexion the values for the hip joint angle are presented. A higher number for I.C. flexion and 1st peak flexion represents a greater range of motion in the hip joint and also a higher contribution from the hip for force absorption. A lower value for TTP indicates a faster shift to the 1st peak flexion of the hip joint.

![Figure 13. Hip flexion and time to peak in Edea and Graf boots.](image)

In figure 14 trunk flexion the values for the trunk angle are presented. A higher number for I.C. flexion and 1st peak flexion represents greater range of motion of the trunk and also a higher contribution of the trunk for the force absorption. A lower value for TTP indicates a faster shift to the 1st peak flexion of the trunk. With the increased height the average TTP increased as well.

![Figure 14. Trunk flexion and time to peak in Edea and Graf boots.](image)
Part II. VGRF

The results from the VGRF analysis of the jump landings in two different figure skating boots are presented in the following figures. Variables which are compared in the figures are maximal impact force, force time integral (the area under the max force-time curve) and time to maximal force (the time between the IC and maximum force). See figure 6 of force-time curve for an illustration of the force variables.

The values for the maximal impact force are presented from two different measuring systems, The Pedar-X system (in figures marked as Pedar insole or P) and the Kistler force plate (in figures marked as Force plate). Values for the force time integral and for the time to maximal force are presented just for Pedar-X measuring system.

For the Pedar-X force examination the foot was divided into separate foot sections: forefoot, midfoot and rearfoot (figure 5) (in figures marked as Pedar insole).

In Figure 15 maximal impact force values for the highest VGRF experienced by the foot during the impact are presented. The higher the force, the greater the demand on the body for force absorption. A greater average force acted during the landing impacts in Graf boot compared with Edea boot. With the increased height the average VGRF increased as well.
Figure 15. Maximal impact force.

In Figure 16 area under the force-time curve the values of force-time integral are presented. A greater average area under the maximal force-time curve was seen during the landing impacts in Graf boot compared with Edea boot. With the increased height the average area under the maximal force-time curve decreased.

Figure 16. Area under the force-time curve.
In Figure 17 Time to maximal force the time values between the IC and maximal VGRF are presented. The subjects reached the maximal force after the IC faster in Edea boots than in Graf boots. With the increased height the average time to maximal impact force decreased.

![Time to maximal force](image)

**Figure 17.** Time to maximal force.
Part III. Figure skating boots

Figure 18. Materials, heel, insole for the Graf boot.

Figure 19. Middle cut Edea boot.