THE EFFECT OF THE SKI BOOT ON KNEE ROTATION MOMENTS IN HORIZONTAL BALANCE PERTURBATIONS

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ABSTRACT

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Alpine skiing is one of the most popular winter sports in the world. Alpine skiing can also be categorized as an extreme sport and is known to be a sport with a high risk of injury (Maes et al. 2002). The ski boot acts as an interface between the skier and skis and transfers the forces from the skier to the skis. This force transfer is strongly influenced by the ski boot's mechanical properties, which affect the skiing and the skiing safety (Hasler et al. 2019). Even if the equipment has a big role in skiing, relatively little published research is available on ski equipment. The main purpose of this study was therefore to examine the acute response of the rotational moments on the knees when wearing ski boots during a simulated balance perturbation. In addition, the acute response of the knee adduction moments and knee flexion angles were studied.

Seventeen healthy (11 men, 6 women), national level alpine skiers (age 16.8 ± 2.1 yr, height 173.1 ± 10,6 cm, weight 68.4 ± 14.1 kg) were recruited in cooperation with the help of Kuopio Region Sports Academy from the local alpine ski gymnasium and the local ski club. The measurements were conducted on an instrumented treadmill and with help of a reflective marker-based 3D motion capture system. The protocol included 10 perturbations with a given direction (anterior-posterior, medial-lateral, lateral-medial) and speed (slow or fast) at random intervals barefoot and with ski boots on.

The absolute maximal rotation moment, adduction moment and flexion angle and the absolute maximal change from the start position to 150 ms were calculated from the mean values of the 10 perturbations. The means and standard deviations were calculated from the maximal values and change values. The means of the maximal values and change values of barefoot and ski boot conditions were compared.

The main findings of this study were that statistically significant differences in knee rotation moments between the barefoot and ski boot conditions were found only in the maximal change in posterior perturbation. The differences in maximal knee adduction moments were statistically significant in every perturbation direction. No statistically significant differences in knee adduction moments were found in the maximal change values. Statistically significant differences in maximal knee flexion angles were found in all perturbation directions and in the maximal changes in the knee flexion angles in posterior perturbation direction.

The results can be applied to several different research aspects, equipment design and development, and training methods, such as balance training.

Key words: alpine skiing, ski boot, knee rotational moments, perturbation, acl

TIIVISTELMÄ

Hellman, E. 2023. Monon vaikutus polven rotaatiomomentteihin horisontaalisissa tasapaino perturbaatioissa. Liikuntatieteellinen tiedekunta, Jyväskylän yliopisto, Biomekaniikan pro gradu -tutkielma, 76 s.

Alppihiihto on yksi maailman suosituimmista talviurheilulajeista. Alppihiihtoa voidaan pitää myös extreme lajina, ja sen tiedetään olevan myös laji, jossa on suuri loukkaantumisriski (Maes et al. 2002). Mono on yksi alppihiihdon tärkeimpiä varusteita, sillä se toimii laskijan ja suksien välisenä liitoskohtana, joka siirtää voimat laskijasta suksiin. Voimansiirtoon vaikuttavat vahvasti monojen mekaaniset ominaisuudet, jotka puolestaan vaikuttavat laskuun ja turvallisuuteen (Hasler ym. 2019). Vaikka varusteilla on suuri merkitys alppihiihdossa, on julkaistuja tutkimuksia varusteista saatavilla suhteellisen vähän. Tutkimuksen päätarkoitus oli tutkia miten mono vaikuttaa polven rotaatiomomenttehin akuutisti simuloidun perturbaation seurauksena. Lisäksi tutkittiin monon vaikutusta polven adduktiomomentteihin sekä fleksiokulmiin.

Seitsemäntoista tervettä (11 miestä, 6 naista), kansallisen tason alppihiihtäjää (ikä 16,8 ± 2,1 vuotta, pituus 173,1 ± 10,6 cm, paino 68,4 ± 14,1 kg) rekrytoitiin yhteistyössä Kuopion seudun urheiluakatemian kanssa paikallisesta alppilukiosta sekä paikallisesta alppihiihtoseurasta. Mittaukset tehtiin instrumentoidulla juoksumatolla ja mittauksista suoritettiin 3D-liikkeanalyysi. Mittausprotokollaan kuului 10 perturbaatiota, jotka suoritettiin paljain jaloin sekä monot jalassa eri suuntiin (posteriori-, mediaali- ja lateraalisuuntaan) eri nopeuksilla (hidas tai nopea).

Absoluuttinen maksimaalinen rotaatiomomentti, adduktiomomentti ja fleksiokulma sekä absoluuttinen maksimaalinen muutos alkuasennosta 150 ms:iin laskettiin 10 perturbaation keskiarvoista. Maksimiarvoista ja muutosarvoista laskettiin keskiarvot sekä keskihajonnat. Paljain jaloin tehtyjen testien ja monoilla tehtyjen testien maksimaalisia arvoja sekä muutosarvoja vertailtiin.

Tutkimuksen päätulosten mukaan tilastollisesti merkitseviä eroja polven rotaatiomomenteissa paljain jaloin ja monot jalassa tehdyissä testeissä ei löydetty kuin maksimaalisessa muutosarvossa posteriorisessa perturbaatiossa. Polven adduktiomomenttien muutosarvoissa havaittiin tilastollisesti merkitseviä eroja kaikissa perturbaatiosuunnissa. Polven maksimi adduktiomomenteissa ei puolestaan havaittu tilastollisesti merkitseviä eroja. Polven maksimi fleksiokulmissa havaittiin tilastollisesti merkitseviä eroja sen sijaan kaikissa perturbaatiosuunnissa sekä muutosarvossa posteriorisessa perturbaatiosuunnassa.

Tutkimuksen tuloksia voidaan hyödyntää esimerkiksi tutkimuksissa, välineiden suunnittelussa ja kehittelyssä sekä harjoittelussa, kuten esimerkiksi tasapainoharjoituksissa.

Asiasanat: alppihiihto, mono, polven rotaatiomomentit, perturbaatio, acl

USED ABBREVIATIONS

ACL	Anterior Cruciate Ligament
ASIS	Anterior Superior Iliac Spine
C	Completion Phase
CGM2	The Conventional Gait Model 2
COM	Center of Mass
COP	Center of Pressure
DKV	Dynamic Knee Valgus
HQ	Hamstring to Quadriceps ratio
I	Initiation Phase
LCL	Lateral Collateral Ligament
MCL	Medial Collateral Ligament
MVC	Maximal Voluntary Contraction
Nm	Newton meter
PCL	Posterior Cruciate Ligament
PiG	Plug in Gait Model
S1	Steering 1 Phase
S2	Steering 2 Phase

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1 INTRODUCTION

Alpine skiing is one of the most popular winter sports in the world. Alpine skiing can also be categorized as an extreme sport and is known to be a sport with a high risk of injury (Maes et al. 2002). Like in other extreme sports, different types of injuries also occur in alpine skiing. The most injured body part in alpine skiing is the knee (Brucker et al. 2014; Ruedl et al. 2009), especially the outer knee (Urabe et al. 2002). The most injured knee parts are the anterior cruciate ligament (ACL) and the medial collateral ligament (MCL) (Brucker et al. 2014; Burtcher et al. 2008). Menisci and lateral collateral ligament (LCL) are not injured as often as the ACL (Kim et al. 2012). Generally, a correlation between the knee injuries and unexpected events, such as loss of balance, abrupt valgus external and internal rotational loading have been found (Bere et al. 2011).

The ACL rupture explains almost half of all serious knee injuries sustained while skiing, and often occurs in a fall or balance loss situation when the long lever arm of the ski applies extreme torque to the knee. (Nusser et al. 2016; Brucker et al. 2014; Burtcher et al. 2008). An other essential piece of equipment required is the ski boot, which acts as an interface between the skier and skis and transfers the forces from the skier through the bindings to the skis. This force transfer is strongly influenced by the ski boot's mechanical properties, which in turn affect the skiing and the skiing safety (Hasler et al. 2019). Even if the equipment has a big role in skiing, relatively little published research is available on ski equipment and in particular the ski boots. Although the ski boot–binding interface has been associated with an overall reduction in knee injuries, the technology does not appear to have positively affected the knee joint (Benoit et al. 2005). The severe ligament injury incidence rate has been tripled from the 1960s to the beginning of the 2000s (Maes et al. 2002) while ankle and tibia injuries have been reduced significantly (Hunter 1999). These 40 years can be said to be the timespan when the ski boots changed the most towards the modern ski boot. Wilson et al. (2021) has stated that when knowing the influence of lower extremity alignment on knee injury, it would seem important to further seek for the relationship between ski equipment and lower extremity alignment.

A lot of medical studies have analysed the relevance of safely adjusted bindings of the common injuries of the knee joint ligaments, but the influence for example of the flexibility of the ski boot and the injury pattern has been neglected (Bürkner et al. 2008). According to Bürkner et al. (2008) further biomechanical studies examining the power transmission from ski boots to the lower leg, especially the rotational loads, are needed. Despite highly developed ski bindings, 62% of all lower leg fractures result from rotational trauma (Bürkner et al. 2008). Also, according to Noé et al. (2009) future research should include kinematic and kinetic analysis to gain understanding how efforts around the joints are involved in postural maintenance with external devices that generate ankle mechanical restrictions such as ski boots. The main purpose of this study is therefore to examine the acute response of the rotational moments in the knees when wearing ski boots during a simulated balance perturbation. In addition, the purpose is to examine the knee adduction moments and knee flexion angles.

2 JOINT BIOMECHANICS

Joints can be defined as a place where two bones meet. All bones in the human body, except the hyoid bone in the neck, form a joint with another bone (Jefferson 2017). The human knee joint has one of the most complicated joint structures from a kinematic point of view (figure 1). If viewed as a mechanical structure, the knee consists of two irregular bearing surfaces, the tibial and femoral condyles which are covered with articular cartilage. Between these two rigid structures lies the menisci. The bones are connected by several ligaments of which the two cruciate and the two collateral ligaments are the most important ligaments. The knee bones are also connected by collagenous fibers organized in a capsule. The main motion of the knee joint is flexion, but also rotation around the longitudinal axis is possible when the joint is not fully extended. The quadriceps muscle group is the most important extensor muscle group in the knee, and it is connected to the patella. The patella is connected to the tibia by the patellar tendon, which increases the lever arm of the quadriceps with respect to the joint. (Huiskes et al. 1985)

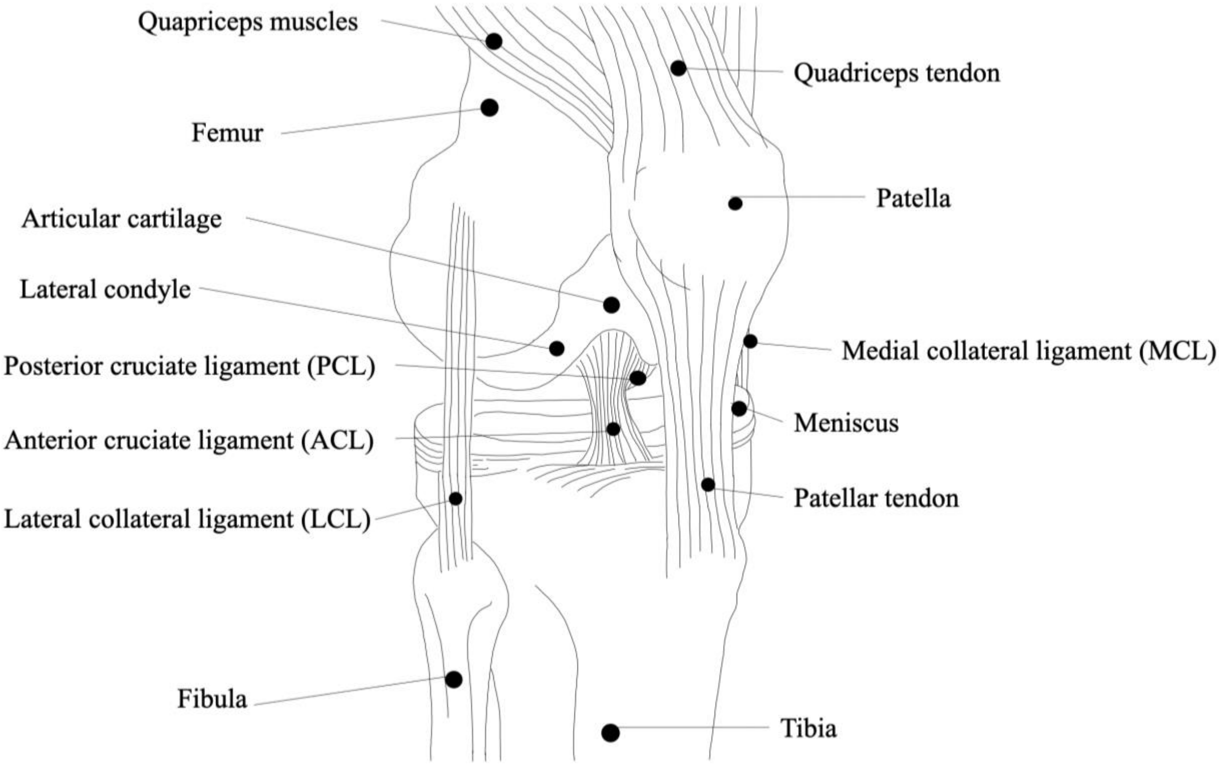


FIGURE 1. The biomechanical structures of the knee. (Referring to Johnson 2008)

The ball-and-socket joint, gliding joints and hinge joints are joints which are most relevant to skiing. The ball and socket joints are the most mobile type of joints, and they consist of a bone with an egg-shaped head which articulates with the cup-shaped cavity of the other bone. These types of joints can be found in the hip and shoulder. The ball-and-socket joints have the widest range of motion of all the joint types, permitting movement in all planes including rotatory movement. The articulating surfaces of the gliding joints are almost flat or slightly curved and can be found in the wrists, ankles and between adjacent vertebrae. The gliding joints allow sliding, back-and-forth motion, and twisting moments. Lastly the hinge joint, which's surface of the convex side fits the concave side. This allows movement only in one plane. The elbow is a hinge joint while the knee can be categorized as a modified hinge joint. (Jefferson 2017)

The joint movements can be divided into flexion, extension, abduction, adduction, rotation, and circumduction. Flexion means bending parts so that the angle between them decreases, for example bending the leg at the knee. Extension means straightening parts at a joint so that the angel between them increases, for example straightening the leg at the knee. At the same time the angle at the frontal plane decreases. In abduction the part is moving away from the midline, for example lifting the leg away from the body to the side of the body. The part e.g., the limb is moving away from the sagittal plane. In adduction the part e.g., the limb is moving toward the midline. For example, returning the leg from the side back to an alignment with the body. In adduction the part is moving toward the sagittal plane. In rotation the part is moving around an axis of a bone, for example twisting the head from side to side. Medial or internal rotation includes movements toward the midline, whereas lateral or external rotation includes movement in the opposite direction. Circumduction is a combination of flexion, extension, abduction, and adduction, where the limb is moving in a circular manner. There are only few joints that are capable of circumduction, for example the hip and shoulder joints. (Jefferson 2017)

2.1 Joint moments

Joint moments describe the net sum of all internal moments delivered by all internal structures around a joint (Sloot and van der Kroogt 2018). Muscles and other soft tissues, like ligaments (when they are stretched), produce moments of force across joints during movements (Thompson 2001). The external joint moments are calculated using external forces, i.e., ground reaction forces (which are applied to the body), the distance from the force vector to the COM, the kinematics of the joints and moments of inertia about the COM. These parameters are also the input variables for the equations to calculate joint moments. (Pandy and Berme 1988)

The total moment at a joint is calculated as the product of 1) the joint segment's moments of inertia, which includes the segment's masses and lengths and 2) the joint's angular acceleration. The direct total moments are the sum of individual moments produced by 1) ground reaction forces, 2) joint reaction forces, 3) muscle and soft tissue forces that produce the joint moment. The ground reaction and joint reaction moments can also be calculated if we have the information on the ground reaction forces, the segment placements and segmental velocities. (Thompson 2001)

2.2 Inverse dynamics

Motion can be described by two different methods, forward dynamics, and inverse dynamics. These two methods connect the kinetics and kinematics and use the presumption of rigid body mechanics (Klous 2007). Inverse dynamics analysis is a commonly used method to investigate aspect of the mechanics, energetics, and control of the movement and to calculate net joint torques in a rigid body linked segment model. It is typically based on measurements of kinematics of the body segment complemented with measurements of external forces such as the ground reaction forces (Faber et al. 2018). This is described in the flowchart for the inverse dynamic approach to determine joint loading in figure 2. The development in computational dynamics have made it possible to estimate forces in the body's internal structures (Damsgaard et al., 2006, Delp et al., 1990).

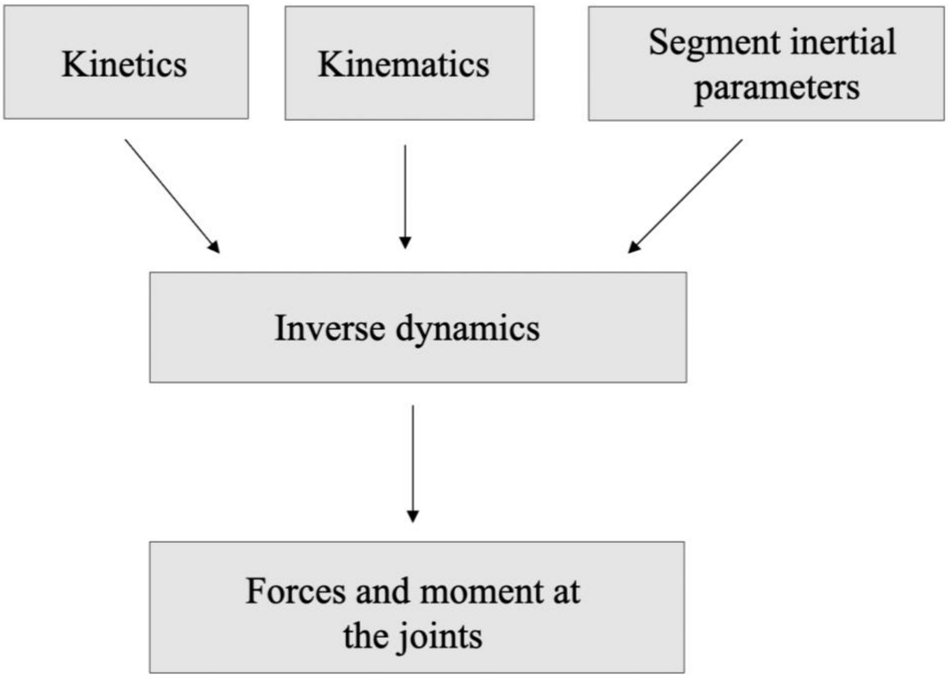


FIGURE 2. Flowchart for the inverse dynamic approach to determine joint loading (Referring to Robertson et al. 2004).

In forward dynamics, forces are the input to the model and the linear and angular accelerations are calculated. When the accelerations are integrated twice, the variables (which describe the movements of each segment) are obtained. In the inverse dynamics the analysis is the opposite to forward dynamics. The movement, i.e., positional and time information, are used as input variables. When the input is differentiated twice, the linear and angular accelerations of each segment are obtained. Now also the resultant joint forces and joint moments on the rigid body segment can be calculated. (Nigg & Herzog, 2007)

In inverse dynamics, the calculations move from distal to proximal. The values from the more distal segment are used as an input for the neighboring more proximal segment (Robertson et al., 2004). To calculate the kinetics of a segment in 3D inverse dynamics, all force and moment calculations must be completed in the local coordinate system of the concerning segment. When the calculations for a segment are done, the force and moment vectors must be transformed to the global coordinate system. Kinematic and kinetic input data are not often collected with equal sample frequencies and the transformation matrix is often determined only with kinematic data. (Klous 2007)

3 BIOMECHANICS OF ALPINE SKIING

There are many forces affecting both the skier and the speed of the skier such as gravity, reaction forces, friction of the ski in both longitudinal and transverse directions of the ski, air resistance, steepness of the slope, momentum, and kinetic energy. In the turn the skier is affected by centrifugal force. When you want to turn the skis i.e., change direction, you need a sufficiently large opposite force, which is called the reaction force. Centrifugal force and reaction force are thus opposing forces to each other. Centrifugal force is directed away from the center of the turn, and the reaction force, in turn, is directed toward the center of the turn. In order to make the skis turn, the skier must direct the force to the sides, towards the center of the turn. If the force is not used until the end of the turn, the movement continues in a straight line (in the direction of the tangent) due to the law of inertia. The reaction force is practically created by pressing the skis on the edge against the surface of the snow, which creates a counter force from the resistance of the surface i.e., the snow. Thanks to the reaction force, the trajectory of the skier is curved. (Gilgien et al. 2013; Peltonen 2010)

The turn can be divided into different phases, with the help of calculating the COM trajectory and the trajectory of the skis or with help of a video analysis. According to previous studies, the turn can be divided either into two (Vaverka et al. 2012), three (Spörri et al. 2012; Supej 2020) or four (Supej et al. 2015) phases. All previous studies have defined the start of the turn, which happens when the point on the COM moves and cuts the ski line. At its simplest, the turn can therefore be divided into two phases, in which case the first phase of the turn is determined to be all movements that take place before the actual turn, where the skier's COM moves straight forward. The actual turn can be determined when the COM line deviates from the straight line, i.e., starts to curve and cuts the ski line (Vaverka et al. 2012). Figure 3. shows the COM line crossing the ski line.

However, the turn is typically divided into three (Spörri et al. 2012; Supej et al. 2020) or four different phases (Supej et al. 2015) (figure 3). In these cases, the start of the turn, i.e., the initiation phase (I) is determined to start from the end of the edge change of the outside ski, i.e., when the ski turns from the inside edge to the outside edge. The turn itself, i.e., the steering phase (S1 and S2), is determined by the increase in the angle of the skis, until the hips and knees reach the maximum angles. The steering phase can be divided into two parts: pre-gate (1) and post-gate (2). The end of the turn, i.e., the completion phase (C) of the turn is defined as all movements after the actual turn and when the skis return to the base (Falda-Buscaiot et al. 2015). In the completion phase of the turn, skis are prepared for the turn switch (Klous et al. 2012). Figure 3 shows the different turn phases.

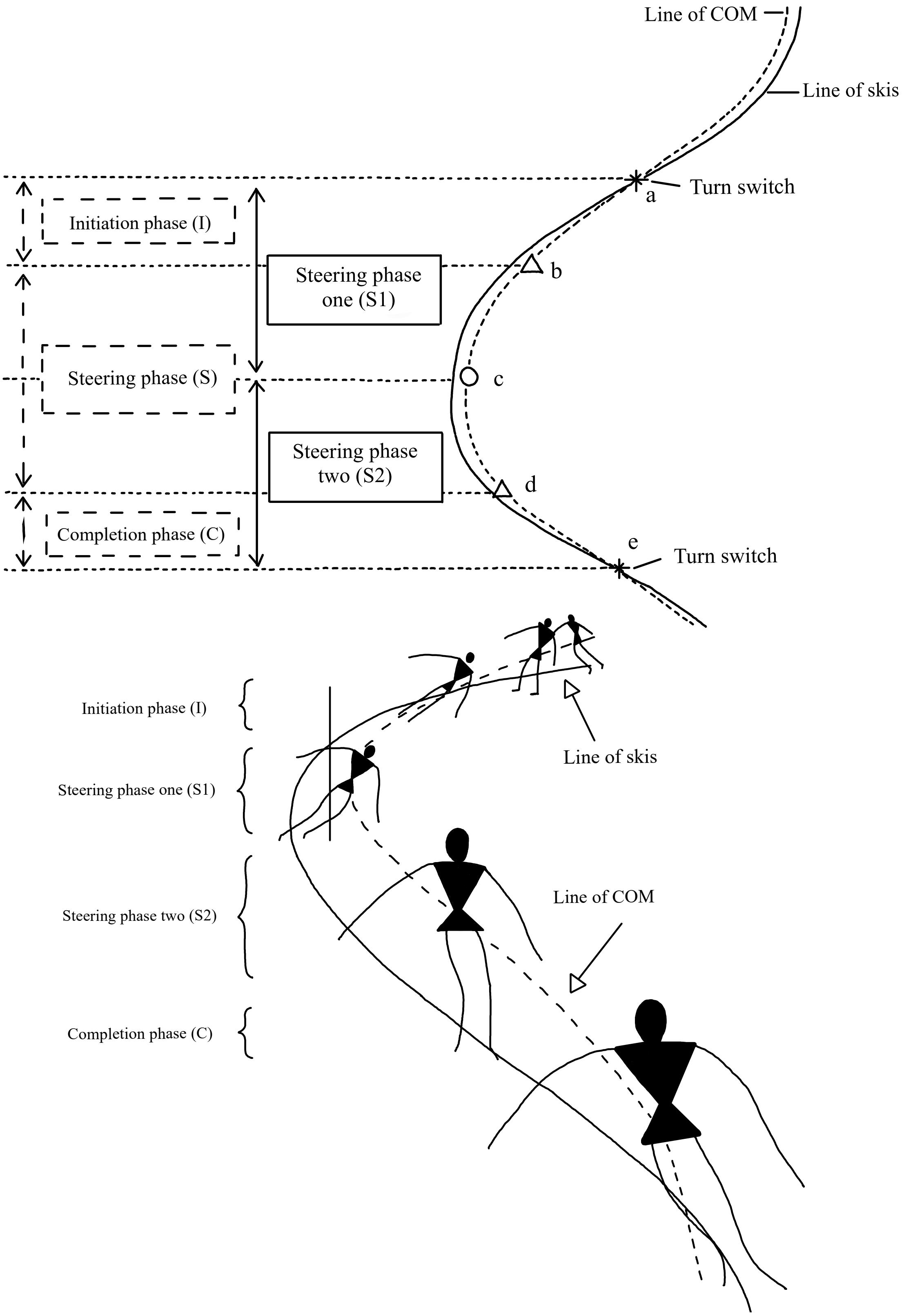


FIGURE 3. Turn phases (Referring to Supej et al. 2015; Supej et al. 2020; Spörri et al. 2012).

3.1 Kinematics and kinetics

Alpine skiing can be viewed kinematically and kinetically. Kinematics studies motion geometrically, without caring about the forces causing the motion. Kinetics, in turn, studies the causes and relationships between the forces acting on the system and the movement they cause (Dusto 2020). In alpine skiing, kinematic variables include for example the line (trajectory of the skis) and speed and kinetic variable's reaction forces, power loss, air resistance and friction (Meyer 2012).

During skiing the pressure is distributed differently on both legs depending on the phase of the turn. For example, in Falda-Buscaiot's et al. (2017) study, the pressure distribution at the initiation phase of the turn was equal, i.e., 50% on both legs, while during the steering and completion phases, the pressure distribution was 75% on the outside leg and 25% on the inside leg. Generating high pressure on one ski (i.e., the outer leg) is a basic requirement if you want to make the ski bend and turn more tightly than what the ski's turning radius indicates (Falda-Buscaiot et al. 2017). This means that both legs have their own role in the turn: both inner and outer leg are responsible for the stability and balance of the landing, although the outer leg has an active role because it is also responsible for ending the turn. In order to make the skiing stable, the skier must be able to control both external forces and the torque that occurs during skiing. The skier may also need more pressure on the inner ski in order to be able to control his balance during the turn. Because of this, the skier should lean even too much on the inside of the turn, if he applies a lot of pressure to the inside ski. In this case however, it would be impossible for the runner to simultaneously maintain both the high externally produced pressure on the inner leg and the balance required for this. Due to the above-mentioned reasons requiring stability, the skier can only generate high pressure on the outside ski. (Falda-Buscaiot et al. 2017.)

In the lateral direction of the foot (medial-lateral), the pressure is usually distributed 40/60% in which case the pressure is stronger on the outer side of the foot (lateral) (Falda-Buscaiot et al. 2017; Nakazato et al. 2011). In ski boot there is only about 1° movement freedom on the plantarflexion-dorsiflexion axis, which affects the lateral movement of the COP (center of pressure) a bit (Petrone et al. 2013).

The COP has been observed to move from front to back (from front to the heel) until the beginning of the steering phase (Falda-Buscaiot et al. 2017; Nakazato et al. 2011; Keränen et al. 2010). The movement of the COP is influenced, among other things, by the steepness of the slope. In Nakazato's et al. (2001) study, COP moved in the front-back direction (anterior-posterior) at the steep part of the slope 271,7 mm and at the flat part 195,5 mm. A greater movement indicates a greater need to control balance (Falda-Buscaiot et al. 2017). When the slope is steep, more pressure is required on the front of the foot during the initiation phase in order to make the turn start quickly. On a flat slope, the pressure is distributed more evenly under the foot, which usually happens because the skier concentrates more on gliding on the ski. However, the pressure on the middle part of the foot is often very small and even due to the arch of the foot. (Falda-Buscaiot et al. 2017.) According to Noé and Paillard (2005) the COP surface is correlated to the center of gravity and can be viewed as an indicator of the subject's or skier's performance. The smaller the surface is, the better the performance. The COP velocity again is an estimate of the net muscular force variations and can that way evaluate the subject's postural control (Noé & Paillard 2005).

3.2 Effect on joint moments

It has been noted that all forces and moments on the knee joint loading are higher at the outer leg in all turn phases. An exception to this is the flexion-extension moment in all turn phases and the internal-external rotational moment in the initiation phase (I) of the turn, which have showed larger average values for the inner leg (Klous et al. 2012). The higher outer leg forces of a carved turn in longitudinal and anterior-posterior direction in the initiation and steering phases of the turn, can be explained by the fact that generating high pressure on one ski (i.e. the outer leg) is a basic requirement if you want to make the ski bend and turn more tightly than what the ski's turning radius indicates and to keep the skis on the edges (Falda-Buscaiot et al. 2017; Klous et al. 2012).

Differences in joint motions in different types of turns i.e., carving, and skidded turns has also been found. The joint motions in carving turns are more moderate with no impact resistance, compared to skidded turns, which helps skiers to make smooth and effective turns (Yoneyama et al. 2000). In short carving turns the skier makes the joint angles change gradually by rotating the thigh, which allows the amplitude of reaction forces to be small, while in short skidded turns the skier makes rapid thigh rotations causing the reaction forces to be more abrupt. The moderate motion without the big impacts in carving turns, aids skiers to make more effective and safe turns. (Yoneyama et al. 2000). In ski racing the majority of he turns are carving turns, but in tight situations and turns also skidded turns are being used.

Anterior-posterior forces have shown similar patterns in both carving and skidded turns. The forces seem to increase until the second steering phase (S2) (≈ 60%) and to decrease after that. In skidded turns the forces increased up to approximately 1.5 times the skier’s bodyweight, when in a carving turns the forces exceed up to 2 times the skier’s bodyweight. Medial-lateral forces show however different patterns for carving and skidded turns. In skidded turns the forces increase up from the beginning of the first steering phase (S1) until the end of the first steering phase (≈ 25–50%). In the carving turns the largest increase has been observed in the second steering phase (S2) (≈ 50–75%) (Klous et al. 2012). It is still important to remember that the joint forces and moments may show significant variation that do not always appear to be systematic or related to the turn phase. These variations could be a consequence for example of the unevenness of the slope and the vibrations of the skis (Klous et al 2012). All the differences between carving turns and skidded turns have been summarized in table 1.

TABLE 1. Joint motions, moments, and forces in carving and skidded turns (Referring to Klous et al. 2012 and Yoneyama et al. 2000).

	Carving turns	**Skidded turns**
Joint motions	• Moderate, no impact resistance • Joint angles changing gradually by rotating the thigh • Knee joint flexion is smaller	• Abrupt, impact resistance high • Rapid thigh rotations • Knee joint flexion is larger
Joint moments	• The knee's flexion-extension moment larger values are higher for the inner leg in all turn phases • The knee's internal-external rotational moment larger values for inner leg in I • All other moments in the knee are higher for the outer leg in all other turn phases	• The knee's flexion-extension moment larger values are higher for the inner leg in all turn phases • The knee's internal-external rotational moment larger values for inner leg in I • All other moments in the knee are higher for the outer leg in all other turn phases
Reaction forces	• Range of the force changes are small • Up to 2 times the skier's bodyweight	• Range of the forces changes is large • 1,5 times the skier's bodyweight
Anterior-posterior forces	• Forces increasing until the S2 (≈60 %)	• Forces increasing until the S2 (≈60 %)
Medial-lateral forces	• Largest increase in S2 (≈50–75 %)	• Forces increasing from the beginning of S1 until the end of S1 (≈ 25–50 %)

3.3 Injuries

Alpine skiing can be categorized as an extreme sport and is known to be a sport with a high risk of injury. The severe ligament injury incidence rate has been tripled from the 1960s to the beginning of the 2000s (Maes et al. 2002) while ankle and tibia injuries have been reduced significantly (Hunter 1999). These 40 years can be said to be the timespan when the ski boots changed the most. Spörri et al. (2016) proved five factors that have a direct relation to injury risk: insufficient core strength or core strength imbalance, high skill level, sex, which is depending on the type of injury, unfavorable genetics, and the combination of highly shaped, wide, and short skis. It has also been speculated that the ski boot pushing forward on the tibia could preload the ACL. The preload coupled with an extreme contraction of the quadriceps muscles to maintain the balance is believed to help the tearing of the ACL. (Herzog & Read 1993)

The injuries in alpine skiing do not always occur during falls or crashes, in fact a big part of the injuries occur during the turn where the skier just loses the balance and do not fall. For example, in Bere's et al. (2011) study nineteen of the twenty analyzed injuries occurred during skiing and only one during a crash. In more than half of the cases, the skier was turning at the time of injury. In all the cases, the skier was out of balance in a backward and/or inward position. The injuries happened mainly in the steering phase. (Bere et al. 2011). In most cases, in alpine ski racing, the ACL injuries happen as a result of the external rotation of the tibia, which forces the knee into an extreme valgus position (Bere et al. 2011; Dai et al. 2012; Ettlinger et al. 1995; Hame et al. 2002; Stasi et al. 2013; Yukio et al. 2002). The knee is typically placed in an extreme valgus position when one ski becomes fixed or loses its parallel alignment with the other ski while the skier is moving downhill. (Yukio et al. 2002) At the time of a fall or loss of balance, the knee can be exposed to three different stresses according to Yukio et al. (2002): (1) an external rotation stress, which is forcing the knee into an extreme valgus position, (2) a stress that forces the knee to a hyperextension, or (3) a stress which is forcing the lower leg to internally rotate. According to Bürkner et al. (2008) 62% of all fractures are caused by rotational traumas. Other typical causes are compression, dorsal forces, and direct collision.

Another well know injury mechanism in alpine skiing apart from the valgus-external rotation mechanism is the phantom foot mechanism, which is claimed to be the most common mechanism for ACL injuries in recreational skiing (Ettlinger et al 1995; Natri et al. 1999), in addition to the slip-catch mechanism and dynamic snowplow mechanism (Bere et al. 2011). The skiing injuries in alpine ski racing differ from recreational skiing, which is not unexpected, as alpine ski racing requires extreme skiing skills, experience, more aggressive equipment, and good overall fitness. The skiing conditions and the terrain are also obviously more challenging in ski racing than in recreational skiing. (Bere et al. 2011).

The phantom foot mechanism happens in a situation, where the skier is out of balance with the hips below the knees. The upper body usually faces down the downhill ski and the uphill arm is back. The actual injury occurs when the inside edge of the tail of the downhill ski is caught in the snow, forcing the knee into an internal rotation in a very flexed position, where the ski acts as a lever to bend or twist the knee. (Bere et al. 2011) According to Hame et al. (2002) a fully extended or fully flexed knee represents the most dangerous loading conditions for knee injury from twisting accidents during skiing.

The slip-catch and dynamic snowplow mechanisms do have a similar end result: internal rotation and valgus of the knee. In slip-catch mechanism, the inside edge of the ski unexpectedly catches the snow surface, which forces the knee into internal rotation and valgus. This loading pattern is related to the self-steering effect of the carving skis. When the edge of the ski catches the snow, the ski acts as a lever to internally rotate the knee. (Bere et al. 2011) In dynamic snowplow mechanism, the ski drifts away from the body's COM when the body attempts to maintain the balance, forcing the skier into a split position, while the weighted ski rolls from the outside edge to the inside edge, which again catches the snow and forces the knee into internal rotation and valgus. (Bere et al. 2011; Ruedl et al. 2009)

The kinematic and kinetic factors which are possible factors for the skier to sustain a slip-catch injury are similar to the risk factors for ACL injuries that have been recognized trough the sport medicine literature, for example the earlier mentioned knee valgus and excess tibial rotation, but also hip internal rotation and hip adduction. (Dai et al. 2012; Stasi et al. 2013) The fact that

ACL injury risk is increased for female compared to male skiers is often connected to the increased prevalence of these risk factors in women (Stasi et al. 2013).

The injury mechanism can be viewed for example with kinematic, skiing load related or skiing technique consideration. In kinematic consideration the central issues could for example be how the injured skier's body parts move and how the lower limb moves relatively to the thigh bone. The typical parameters for this kind of kinematic consideration could be explained with typical parameters such as tibia rotation angle acceleration, temporal course of the reflexion angle or with the trajectory of the body's COM. In skiing load related consideration, the central issues could for example be which resultant forces and moments work on the skis or where the application points of the resultant force are. Typical parameters in skiing load related considerations are for example the time related reactive loads between the ski boot and the binding. Also, the skiing technique can be used as an aspect when categorizing skiing injuries. The main issues could for example be what the skiing technique and styles were or what kind of errors and corrective measures happened. Typical parameters in this kind of considerations are for example the position and movement of the skis relative to each other or movements relative to certain joint axes. (Senner et al. 2013)

It is possible to prevent injuries in alpine skiing for example with physical preparation such as strength training for legs and core, postural balance training, and simulated balance training (Ashker et al. 2017; Herzog & Read 1993; Kovacs et al. 2004; Malliou et al. 2004; Senner et al. 2013; Spitzenpfeil et al. 2005; Spörri et al. 2016; Spörri et al. 2017; Taube & Gollhofer 2016) Anyhow, it is also possible at least reduce ski injuries with equipment adjustments. If we look at the injury mechanisms, there are relatively few effective mechanisms to alter balance or frontal plane lower extremity alignment, to reduce edge catches or prevent fall or injury-causing movement patterns with help of equipment. (Senner et al. 2013) However, Senner et al. (2013) proposed some solutions, which include reducing the ski's side cut, shortening the skis, lowering the binding height, adjusting the orientation of the boots relative to the skis in the transverse plane, and adjusting the boot's cuff angle relative to the lower shell.

4 SKI BOOTS

The alpine ski boot consists of different parts: the shell, which includes the hard (thermo)plastic outer shell, which can be divided to the lower shell or the base, the cuff (and sometimes a rear spoiler), the outer sole, pivot and the buckles and a power strap, and the soft liners, which include the tongue, the insoles and sometimes a rear spoiler (figure 4). The alpine ski boot has been optimised again and again over many years and that has influenced the skiing techniques pretty much. Some of the most innovative milestones in the ski boots history are for example the change from the leather upper to a plastic shell and the change from laces to buckles or the arrival of the rear spoiler in the 1970s. (Senner et al. 2013) After the 2000s the ski boot hasn't really changed that much, mainly the colour, the liner and the buckles seems to change a bit season after season. Compared to the old leather boots, the new plastic boots have a significantly stiffer and higher cuff, appear to protect the foot and lower leg better. Together with the improved release bindings, the tibia and ankle injuries have decreased. Apparently, this change in the technology has led to a shift in the injury location towards the knee. (Senner et al. 2013)

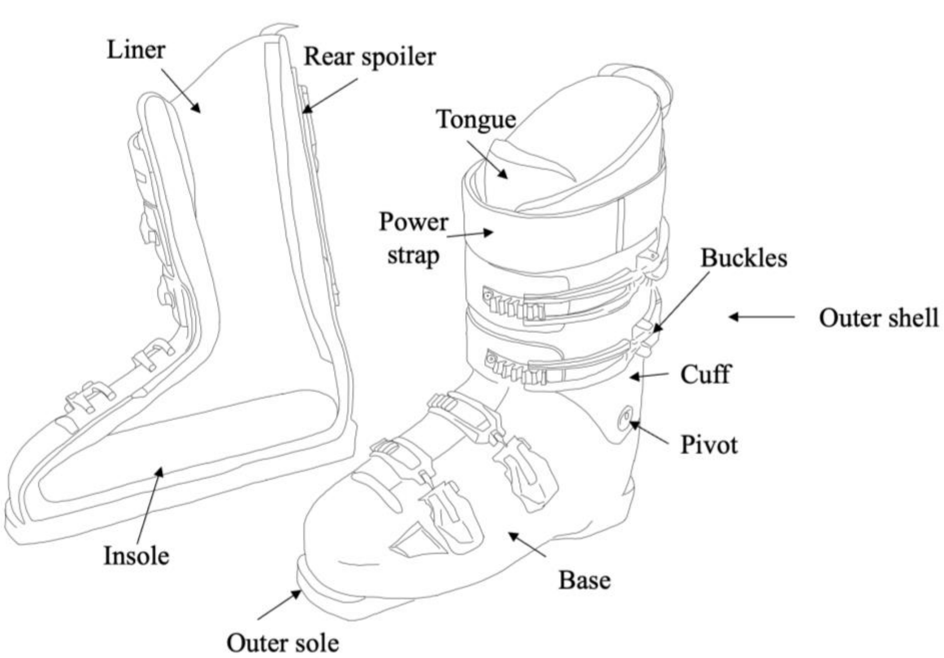


FIGURE 4. The anatomy of a ski boot.

The ski boot is often defined as the most important equipment in alpine skiing. Ski boots are crucial in transferring the load from the skier to the skis jointly with the bindings. The ski boots allow the skier to maintain control over the skis and to perform for example turns, stops and jumping. (Lann vel Lace & Błaźkiewicz 2021) They also protect the the foot, ankle, and lower tibia from injuries due to overloads during skiing and falls (Colonna et al. 2013; Lann vel Lace & Błaźkiewicz 2021) and as earlier mentioned ski boots also absorbs shocks (Colonna et al. 2013). In skiing, the safety and performance can depend on really small details, and because of that it would be important to concentrate even on the small details, such as the properties of the ski boots. For example, Nimmervoll et al. (2021) suggested that by measuring the forces within the ski boots, which represent the necessary force transmitting interface during skiing, it could be possible to help skiers to enhance the performance and more importantly their safety. Reducing injuries with help of the equipment adjustments is possible. For example, Senner et al. (2013) proposed a few solutions regarding the equipment adjustment and more accurately, the adjustment of the ski boot: adjusting the orientation of the boots relative to the skis in the transverse plane and adjusting the cuff angle of the boot relative to the lower shell. However, the research in injury prevention in alpine skiing hasn't really been concentrating on the ski boot. According to Bürkner et al. (2008) for example both the influence of the flexibility of the ski boot and the injury pattern has been neglected.

4.1 Features and properties of the ski boot

The ski boot can be adjusted in many ways with the help of changing the cuff or sole angles or by changing the stiffness of the boot by using for example different thicknesses of plastics or different types of plastics. But even if the ski boot is often defined as the most important equipment in alpine skiing because they are crucial in transferring the load from the skier to the skis together with the bindings (Lann vel Lace & Błaźkiewicz 2021), there is still no standardized value for example the flexibility of ski boots (Bürkner et al. 2008; Colonna et al. 2013; Petrone et al. 2013). Without standardized values, it is relatively difficult to compare the effects of the ski boot on the skier's performance and safety. According to Spörri et al. (2017) the ski-binding-boot system is also one of the top five reasons to cause severe injuries in alpine skiing.

Stiffness. As said the ski boot is an essential part of the ski-binding-boot system, which acts as a force and torque connection between the skis and the skier. The transfer of torque and forces are among many other parameters affected by the flexion stiffness of the ski boot. For example, a ski boot with a high flexion stiffness leads often to a more direct force transmission and therefore a more aggressive ski-snow interaction. (Immler et al. 2019) A more aggressive ski-snow interaction has been proven to be one of the factors causing knee injuries (Immler et al. 2019) and, in an addition, a higher flexion stiffness can lead to a more upright or backward skiing position which can cause higher knee loads (Schaff & Hauser 1993) and it has been suggested that a higher flexions stiffness could be an important risk factor in ACL injuries occurring during jump landings (Eberle et al. 2017). Although a high flexion stiffness seems to be a big risk factor, it has also been proven that a low flexion stiffness may affect safety issues. For example, if the flexion stiffness is too low to limit the excessive ankle dorsiflexion (above 40°), it may result ankle injuries (Shealy & Miller 1989). A too low flexion stiffness can also impair the binding release, since a low flexion stiffness might delay the upward force which is needed for the binding to release properly (Immler et al. 2019).

That is to say that the flexion stiffness is a really important factor when choosing the right ski boots for the skiers on different levels. When looking at the technical specifications at the ski boots, most manufacturers report only their own ”flex index”, which is associated with the forward flexion stiffness of the ski boot. The ”flex index” definitions has not been standardized (ISO 5355; ISO 11088; Petrone et al. 2013; Reichel et al. 2008). Some manufacturers such as Salomon, Head and Nordica has reported that they use a scale which shows the force in Newtons that you need to bend the cuff of the ski boot forward by 1° (Bürkner et al. 2008). Still in most cases no information on the test method, the type of test bench or testing temperature is reported by many of the ski boot producers, when they communicate the”flex index” (Colonna et al. 2013). It would be recommended that the flexibility of ski boots would be internationally standardized, in order to make it easier for the skiers to compare the ski boots. (Bürkner et al. 2008)

Boot position. The position of the ski boot is important since many skiers tend to have valgus or varus leg alignments (Colonna et al. 2013). One solution to overcome the problem of the unnatural knee postures is the canting mechanism, which is provided by many ski boot manufacturers. Canting enables medial and lateral tilting of the cuff respective to the base of the boot. It can be achieved by milling the outer sole or changing the position of the cuff with respect to the base of the boot, by putting a wedge under the sole or by using a canting system, which is positioned in the hinge point between cuff and base. (Böhm & Senner 2008; Colonna et al. 2013; Senner et al. 2013; Wilson et al. 2021) According to Wilson et al. (2021) medial canting can significantly decrease in addition to knee valgus also hip internal rotation and hip adduction. Medial canting can also improve some postural control measures which are associated with balance quality, and reduce the activation levels of the Vastus Lateralis, Tibialis Anterior and Biceps Femoris muscles. The canting mechanism appears to also be an appropriate option for improving balance in alpine skiers at least in laboratory settings. As a summary medial canting seems to change the skier's kinetics and kinematics in a positive way, which could reduce the risk of ACL injury. (Wilson et al. 2021)

A foot rotation in the transversal plane has also a small kinematic effect on the knee joint. When wearing ski boots fixed to the bindings, the foot might be in an unnaturally straight position (0°), pushing the knee into a small internal rotation. To overcome this problem Fischer (Ried, Austria) developed the Soma-Tec system, which allows the foot bed to rotate to a so called ”natural V-position” (8° exorotation). Nevertheless, no physiological neutral 0-position of the foot rotation in the transversal plane is known and, in addition, it can be expected that with larger angular adjustments, boundary forces will take place in alpine skiing and this approach has only a low potential to prevent knee injuries. (Senner et al. 2013)

In terms of anterior-posterior movement range besides the ski boot stiffness, a flexible rear spoiler has been developed by Senner (2001) and Lange ski boots. The idea of the flexible rear spoiler is to decrease ACL injuries by flexing the spoiler when the backward moment exceeds a certain threshold value, which permits a reduction in tension forces on the ACL. (Senner et al. 2013) The flexing of the spoiler might also increase the hamstring muscle activity, which has also been shown to reduce the ACL injury risk. (Ashker et al. 2017; Herzog & Read 1993; Senner et al. 2013) In addition to influencing kinematic and kinetic knee injury risk factors, ski boot's frontal plane adjustments might also affect the balance and postural balance (Noé et al. 2018A; Noé et al. 2018B).

Other things that could affect the performance and safety is the for example the height of the ski boot, the liner, and the sole. The height of the ski boot should be high enough to make the force transmission via shins possible, the high cuff also protects the ankle and Achilles tendon (Senner et al. 2013). The liners are often mouldable to fit better and to feel more comfortable, also thermal insulation and microclimates, such as moisture-absorbent layers, are often used. The adaptations of the liners are not only beneficial for comfort but also for safety. A good fitting liner and ski boot makes better power transmission possible and warm feet are a necessity for the sensimotor functions to work. (Senner et al. 2013) The insole is often also mouldable and easy and often more cheap way to get the ski boots to fit better. The outer sole and its abrasion in turn, has been found to be an independent risk factor for ACL injuries (Posch et al. 2019). The features and properties of the ski boot and their effect on the knee joint injuries discussed in this chapter are summarized in table 2.

TABLE 2. Features and properties of the ski boot and their effect on the knee joint injuries (Referring to Ashker et al. 2017; Colonna et al. 2013; Herzog & Read 1993; Immler et al. 2019; Lann vel Lace & Błażkiewicz 2021; Posch et al. 2019; Senner et al. 2013; Shealy & Miller 1989 and Wilson et al. 2021).

Properties	Features	Infuence on knee joint injuries	Comments
Stiffness	• **High flexion stiffness:** more direct force transmission and more agressive ski-snow interaction → a risk factor for knee injuries, more upright or backward skiing position → higher knee loads • **Low flexion stiffness:** does not limit the excessive dorsiflexion (> 40°), impairs the binding release by delaying the upward force which is needed for proper binding release	Yes	• Individual influence • No standardized values existing
Canting	• **Medial canting:** decreases the knee valgus, internal hip rotation and hip adduction, improves postural control measures	Yes	• Individual influence on knee joint kinematics
Exrotation system	• Allows the foot bed to rotate to a ”natural V-position” (8° exorotation) • Does not push the knee into internal rotation	No	• Only limited movement amplitude (<10°) • No physiological neutral-0 position defined in the transversal plane • At larger angle setting constraining forces might occur
Spoiler	• **Flexible rear spoiler:** flexes when the backward moment exceeds a certain treshold, which permits reduction in tension forces of the ACL, spoiler flexing might also increase the hamsting muscle	Yes	• Not widely used • Individual influence

	activity (reduces ACL injury risk)		
Height of the boot	- Should be high enough to make the force transmission via shins possible - Protects the ankle and Achilles tendon	No	- Reducing the height to allow plantar flexion could affect rotational moments in a positive way, but would not the protect the ankle and Achilles tendon
Liner	- Optimisation of fitting, warmth and comfort properties - Good fitting liners enables better force transmission and keeps the feet warm	Unclarified	- Positive influence on sensimotor system - Warm feet are necessary for sensimotor functions to work
Sole	- **Insole:** Optimisation of fitting and comfort properties - **Outer sole:** Abrasion has been found to be an intependent risk factor for ACL injuries	Yes	- Cheaper way to customize the ski boot

4.2 Effect on joint moments

In the modern strongly form fitting ski boot the range of motion is restricted (Chaudhari & Andricchi 2006; Nimmervoll et al 2021; Noé & Paillard 2005). The restriction is affected by many parameters, such as the cuff height and geometry, temperature, material properties and hinge point (Nimmervoll et al 2021). The future ski boot has also a quite aggressive forward lean and high cuff stiffness, which are important features for good skiing performance and reduction of injuries of the ankle joint and tibia, but at the same time these features are factors which can be related to an increasing ACL injury risk (Hauser & Schaff 1987). According to Lann vel Lace and Błażkiewicz (2021) ski boots cause changes in the ranges of angles in the lower limb joints and increase muscle torques in the knee and hip joints, but they do not increase the load on the joints. Ski boots do also cause significant valgus and external rotation misalignment of the knee as mentioned earlier, which may increase especially the risk of ACL injury. (Chaudhari & Andricchi 2006; Böhm & Senner 2008) It has also been speculated that the knee misalignments, caused by the ski boot, put extra pressure on the muscles around the knee and possibly increase muscle imbalances and even patella grinding. (Böhm & Senner 2008; Davey et al. 2019)

4.3 Injuries

It has been speculated that ski equipment and especially the ski boots have a big role in alpine skiing injury mechanisms (Spörri et al. 2012). For example, Herzog and Read (1993) argued that the ski boot pushing forward on the tibia could preload the ACL. The preload combined with an aggressive contraction of the quadriceps muscles to maintain balance is believed to be instrumental to the tearing of the ACL (Herzog & Read 1993). The term ”Boot-Induced Anterior Drawer” tries to summarize this shift of the lower leg towards the front of the leg relatively to the thigh (Senner et al. 2013). It is also widely reported in the literature, that the angles of tibia and foot respectively to the base of the ski boot and the pressure of the foot on the base of the ski boot are responsible for ski injuries. (Schneider 2003; Maes et al. 2002) The ski boot does clearly cause some kind of misalignment and it might also be speculated that this causes extra pressure on the muscles around the knee and possibly increases muscle imbalance and patella grinding (Lann vel Lace & Błazkiewicz 2021).

Böhm and Senner (2008), Senner et al. (2013) and Wilson et al. (2021) proposed some ski boot-based mechanisms to reduce skiing injuries, such as adjusting the boot cuff relatively to the base of the boot in medial-lateral or anterior-posterior direction or adding wedges under the sole and changing the adjusting of the boot relatively to the ski in the transversal plane. However, Böhm and Senner (2008) noted that the cuff alignment impacted valgus position in the knee significantly, but it could only correct the misalignment by 10%. Wedges in shoes that raise the medial side of the foot have been observed to reduce ankle eversion and knee abduction moments in some individuals in running (Nigg et al. 2003) and for example knee abduction moments and balance in alpine skiing (Wilson et al. 2021).

The ski boots have their own role also in falls during skiing. As the skier falls back, the boot cuff is not free to rotate, and the rear spoiler resists the natural motion of the shank. This causes a resultant anterior shear force at the tibial plateau as the upper body and thigh tend to rotate in the opposite direction. This same mechanism happens when the skier lands from a jump in a rear weighted position or when the rear of the skis hit the slope first. The skis tend to rotate down so that they lay flat on the surface while the upper body resists to move. If the lower leg is forced to rotate with the ski, the ACL will be strained and often also injured. This mechanism is called the” boot induced” injury. (Benoit et al. 2005)

5 MUSCLE ACTIVITY, BALANCE, AND POSTURAL CONTROL

The term “balance” describes the dynamics of body posture to prevent falling (Winter 1995). Balance can be described as the action of maintaining the position of the body’s COM vertically over the base of support (Hrysomallis 2011). Traditionally balance control is divided into static balance control and dynamic balance control. Static balance control is defined as the center of mass movements which maintain the balance, while the support base remains stationary. In dynamic balance control both the center of mass and the support base are moving (Shumway-Cook & Woollacott 2016). This traditional definition does not capture all the important aspects of balance control. Shumway- Cook and Woollacott (2016) have suggested that postural balance control can be divided into four different types instead of two: static steady-state balance, dynamic steady-state balance, proactive balance and reactive balance. Static steady-state balance means how to maintain a steady position while sitting or standing while dynamic steady-state balance means how to maintain a steady position during movements such as walking. Proactive balance is a prediction of a predicted postural disturbance and reactive balance a response to an unpredicted postural disturbance (Shumway- Cook & Woollacott 2016).

Perturbation again is a disturbance of motion, that is produced by some force additional to that which causes its regular motion. Perturbations can also be divided into internal or external perturbation. Internal perturbations are caused when the individual fails to control the COM-base of support relationship during voluntary movement. External perturbations again are caused by forces outside the individuals’ control (e.g., being pushed or pulled). (Robbins et al. 2017)

Balance tests are gaining increased importance in both medical and sport sciences. Coordination and proprioception training are now being utilized not just for optimizing athletic performance but also as an essential aspect of children’s skill development and rehabilitation programs for various orthopaedic (such as cruciate ligament tears, joint replacement, and arthrosis) and neurological conditions (including Alzheimer’s disease, dementia, and stroke). Additionally, there is potential for these tests to be used as diagnostic tools, with ongoing research efforts in this area, according to Petró et al. (2018).

To measure required parameters for postural balance assessment, for example center of pressure (COP), there has been an increase in use of instrumented treadmills (treadmills with integrated force sensors). The COP surface correlates to the center of gravity and can be observed as an indicator of the athlete's performance. The smaller the COP surface, the better performance, because the COP is an estimate of the net muscular force variations, and that way evaluates the athlete's postural control (Noé & Paillard 2005). To measure and monitor balance we need force plate data, which are integrated in the instrumented treadmills (Rieger et al. 2021). Instrumented treadmills have become more accessible, which makes it possible for an increasing number of researchers and clinical practitioners to perform dynamic postural measurements to assess static and dynamic steady-state, proactive, and reactive balance (Lesch et al. 2021).

The reliability and validity of dynamic balance tests using perturbations have been studied to some extent. The reliability of these tests is essential for comparing groups or examining changes over time, particularly in response to disease progression or treatment. Studies have found that there is a learning effect in balance responses to external perturbations, which could negatively impact reliability (Lysholm et al. 1998). While the reliability of the outcome measures of balance performance is mostly moderate (varying from modest (Lesch et al. 2021) to excellent (Zemková et al. 2016)) it has been noticed that there are repeatable patterns in the shape of the COP trajectories within a subject. (Lesch et al. 2021) However, some protocols show poor reliability (Robbins et al. 2017) when outcomes are calculated per individual trajectory. On the other hand, the validity of these tests may vary depending on the construct being measured, as different tests might measure task-specific sensimotor skills rather than dynamic postural stability (Ringhof and Stein 2018).

5.1 Muscle activity and balance in alpine skiing

Muscle activity. During skiing, all three muscle work methods are used (eccentric, concentric and isometric). In eccentric muscle work the muscle-tendon complex is lengthening, while in concentric muscle work the muscle-tendon complex is shortening. In isometric muscle work the muscle-tendon complex does not noticeably change length. Muscle work is done against gravity and centrifugal force when the skier performs movements to make the skis change direction and to control the speed. In alpine skiing, the dominance of eccentric muscle work is mostly based on the laws of physics. During the turn, muscle work (reaction forces) is done against a counter force, i.e., the centrifugal force, in which case the muscle work is mostly braking, i.e., eccentric. For example, when skiing, the skier accumulates speed and kinetic energy, which puts pressure for example on the knee extensors, which is why the skiers must resist the forces, i.e., do eccentric work. (Kröll 2015.) Greater forces are achieved in eccentric muscle work than in isometric and concentric muscle work (Enoka 2015).

In alpine skiing, as a result speed and forces, the impacts are also large and require shock absorption, which also affects the muscle work method used. At the initiation phase of the turn, the muscle work is eccentric, in the steering phases of the turn isometric and towards the completion phase, the muscle work becomes concentric (Kröll et al. 2015; Ropret 2017.) However, most of the time the muscle work is eccentric. According to Ropret's (2017) study, the proportion of eccentric muscle in the entire turn is about 85% in slalom and about 88% in giant slalom. According to a study by Alhammoud et al. (2020), during the turn, m. rectus femoris neither lengthens or shortens, m. vastus lateralis lengthens at the beginning of the turn (eccentric phase) and shortens during the turn switch (concentric phase). Also, according to Alhammoud et al. (2020), most of the muscle work performed by the m. quadriceps femoris during the turn is eccentric.

One permanent finding in alpine skiing is that there is high level of effort by the knee extensor muscles, i.e., the quadriceps muscles, during skiing. Many researchers have reported that maximum muscle contraction forces can reach up to 100 – 150% of the MVC in the outside leg during the turn. (Berg et al. 1995; Hintermeister et al. 1997). Müller and Schwameder (2003) stated that m. vastus lateralis show co-loading for the inside ski during carving turns in ski racing. Kröll et al. (2010) investigated specific functional demands of the different knee extensor muscles in recreational skiing. The results for the vastus lateralis muscle did not support the co-loading function for recreational skiing in Kröll's et al. (2010) study. The vastus lateralis muscle seems to be relatively inactive for the inside leg. Anyhow, Kröll et al. (2010) showed instead that the functional demand for rectus femoris muscle of the inside leg is high in recreational skiing (Kröll et al. 2010). Summarized this means that also the inside leg has muscle activity during the turn and has its own responsibilities in both ski racing and recreational skiing.

When the spine is subjected to perturbations, neuromuscular responses, for example reflex muscle contractions take part to the overall balance control and spinal stabilization mechanisms. The responses are affected by for example muscle fatigue, which triggers changes in muscle recruitment patterns. (Abboud et al. 2016). When skiing, being fatigued at some point is more or less unavoidable, it is expected that in order to maintain muscle power output required for skiing at a specific or constant pace, more motor units should be recruited or excited at higher frequencies as they become fatigued. The fast twitch fibers are more sensitive to fatigue than the slow muscle fibers (Komi and Tesch 1979) and increased recruitment should occur for these specific fibers. In recreational skiing, the skier often reduces the muscle power output, when being tired, instead of recruiting or exciting more motor units. This has been shown for example in Kröll's et al. (2011) study, where the EMG frequency decreased and intensity changed for the investigated muscles, which was caused by altered timing or coordination within the turn. Causing most likely a more uncontrolled skiing technique. (Kröll et al. 2011)

Balance. Balance can be described as the action of maintaining the position of the body's COM vertically over the base of support. It is commonly accepted that balance is one of the most important motor abilities in alpine skiing (Hrysomallis 2011). Although the importance of overall balance in skiing is somewhat known, the importance of different balance indices such as mediolateral- and anteriopostural-balance are rarely mentioned. (Hydren et al. 2013)

The velocity changes during skiing constantly because of i.e., the acceleration, due to inertia, the skier's body tends to lean backward for positive accelerations and respectively lean forward for negative accelerations. Therefore, the skier's ability to resist these kind of perturbations is directly related to anteriopostural stability. (Lesnik et al. 2017) Medio-lateral balance is thus affected mostly during the turn, when the skier must lean toward the center of the turn in order to compensate the centripetal force. (Hydren et al. 2013) Last but not least since skiing terrain is often not flat, the balance is constantly disrupted. For this reason, it seems logical to think that the skier's ability to maintain good balance determines performance at least a bit. (Leskin et al. 2017)

One of the most critical aspects in skiing is the ability to perform a sharp turns and resist the forces, which are generated during the turn, while maintaining balance and edge control (Hydren et al. 2013). Even small changes in the body's COM make it difficult to maintain balance when doing carving turns. Bambach et al. (2008) indicated that extreme deviations to the side in the body's COM can provoke falls, since skis driven on the end bend more under pressure. Due to significantly shorter carving/slalom skis, the need for balance control is increased, also in forward and backward directions. Only an optimally coordinated tuning of the muscle use makes it possible to maintain the necessary balance during carving turns. (Mildner et al. 2010.) That is to say, that modern (i.e., carving) techniques need a strong sense of lateral and forward-backward balance because of the big inward leaning body angles (Müller & Schwameder 2003; Raschner et al. 2001).

Hrysomallis (2007) reviewed alpine skiing, as well as other different sports, and found that weak balance skills could be associated with an increased risk of injuries. Furthermore, Steinberg et al. (2016) demonstrated that fatigue during anaerobic performance leads to balance deficits that can cause injuries. Malliou et al. (2004) showed that specific indoor balance training can be beneficial in learning alpine skiing.

Physical training. The importance of strength and balance training has been proven several times. For example, Ettlinger et al. (1995) developed a knowledge-based training program that reduced the injury risk among ski patrols and ski instructors by 62%. The program focused on improving psychomotor skills to develop the awareness of the events leading to ACL injuries. Studies have also shown that specific injury prevention programs, which include neuromuscular training, reduce the risk of ACL injury in other sports, such as football and handball (Myklebust et al. 2007; Soligard et al. 2008).

In alpine ski racing, the skiers must edge their skis with precision. To obtain the correct feeling for carving, optimal sensimotor abilities are needed. For example, continual small lateral and forward-backward adjustments in response to turning radii, speed changes or snow and terrain conditions are necessary. Moreover, because of the different turn radii and speeds in the different disciplines crate strong kinetic forces, the maintenance of balance under the challenging situations is critical for both injury prevention and performance (Spitzenpfeil et al. 2005; Spörri et al. 2017; Taube & Gollhofer 2016).

High postural balance is important for many daily activities, but also to obtain good performance and to avoid injuries in many sports. Especially in alpine skiing, postural exercises are used in training programs for elite skiers. Postural control training can also improve postural performance in healthy and non-injured athletes. (Kovacs et al. 2004). Spörri et al. (2016) found that among other things, lacking core strength or core strength imbalance have a direct relation to injury risk in alpine skiing. Therefore, it is important to concentrate also on core strength and postural balance in physical training in alpine skiing.

Ski racers require high lower extremity muscle strength and for example low quadriceps muscle force is not recommended in general. However, in cases where the ACL force is maximal or in situations where ACL injury could be possible, the quadriceps muscle force should be reduced at the right time. That means that it would be important to be able to adjust and control the quadriceps muscle forces at different occasions in skiing. The line of action of the quadriceps muscle tensile force depends on the flexion angle of the knee, which means that contractions of the quadriceps muscle should be avoided at a stretched knee. This kind of issue could be solved for example by utilizing the whole range of motion of the knee joint or by practicing silent or soft-landing movements. (Spörri et al. 2016). It has been shown that in simulated drop jumps, the quadriceps muscle force at the time of the ground reaction force, which might correspond with the time of maximal ACL force, can be reduced by reducing the landing height (Mokhtarzadeh et al. 2013). In alpine skiing, the equivalent landing height can be reduced by lowering the take-off angles and by increasing the steepness of the landing areas. (Eberle et al. 2017; Schindelwig et al. 2015)

Respectively it has been suggested that the high hamstring muscle force at the time of high ACL force could reduce the risk for ACL injuries (Herzog & Read 1993). For example, it has been showed that hamstrings activation reduces the risk of ACL injuries during landing movement in downhill skiing. Thus, higher activation of the hamstrings can also reduce maximal ACL forces during landing. (Senner et al. 2013) The hamstring to quadriceps ratio (HQ) actually related to knee injury risk according to Ashker et al. (2017). The HQ ratio is also gender dependent and is related to the tendency to knee injury the lower the HQ is. (Ashker et al. 2017)

5.2 Ski boots, muscle activity and balance

As mentioned earlier, the ski boot restricts the range of motion which can again affect the muscle activity. Modern ski technique requires that the skier has a good balance and edges his or her skis with precision. The stiff ski boots make the power transfer to the skis, possible but they may also make it harder to balance. (Mildner et al. 2010) Very stiff ski boots can also act as an external ankle support which mechanically restricts the ankle motion and immobilize some muscles such as the gastrocnemius (Hauser & Schaff 1987). Thus, the effects of such immobilization can be similar to those induced by braces and for example restriction of ankle moment has a harmful effect on postural control (Schaff & Hauser 1989; Caron et al. 2000; Asseman et al. 2004) or at least influence the postural control in some way (Bennell & Goldie, 1994; Hadadi et al., 2011; Mildner et al. 2010; Noé et al. 2003; Noé et al. 2009; Noé et al. 2018A; Noé et al. 2018B; Panwalkar & Aruin, 2013; Tchórzewski et al. 2013). For example, according to Noé et al. (2020) wearing stiff ski boots do not affect negatively on the postural control, but rather suggests a less active postural control. Noé’s et al. (2009) study showed also that the mechanical effects of wearing ski boots are compensated by changes in postural strategy trough the reorganization of muscle coordination. Ski boots can for example improve lateral balance because they restrict ankle inversion and eversion but at the same time limit anterior and posterior control strategies by reducing dorsiflexion (Noé et al. 2018B).

Ski boots also give mechanically efficient support at the tibia level (Noé et al., 2003; Schaff & Hauser 1987) and provide additional tactile stimuli which is sensed by cutaneous receptors at the ankle foot complex (Schaff & Hauser 1987). It is known that somatosensory information, such as tactile stimuli, provided by external support devices improves postural control and decrease postural sway (Rogers et al., 2001). The increased length of the support base caused by the ski boot cuff can also facilitate the upkeeping of the standing posture and decrease the amplitude of postural sways (Pai and Patton, 1997). For example, in Noé’s et al. (2007) study the results revealed that the mechanical effects due to wearing ski boots did not affect the postural balance, in fact the COP area was even smaller when wearing ski boots in the standing posture compared to standing posture without ski boots. An explanation for this could exactly be the same as Pai and Patton (1997) suggested: maintaining the standing posture was facilitated with ski boots by increasing the length of the supporting base.

As we can conclude, the ski boots do significantly influence balance and muscle activity. In addition to general physical training, skiers should utilize both general and ski-specific balance and sensimotor training which could help injury prevention, especially knee injuries. (Mildnet et al. 2010) The balance training should be reduced when the skier grows or improves the skiing skills. In fact, at the more advanced level the skier is, the more balance and sensimotor training should be executed, according to Noé and Paillard's (2005) findings. Their study showed that national level skiers performed worse in postural performance tests without ski boots than the regional level skiers, which might illustrate the long-term effect of wearing ski boots a lot, which impairs postural performance by restricting the range of motion of the ankle joint. Regional level skiers might be less affected by this effect because they spend less time training in ski boots. (Noé & Paillard 2005) According to McGuine et al. (2000), individuals with decreased postural performance might be more prone to ankle injuries than individuals with better postural control. Hence, especially higher-level skiers could benefit from specific training aimed at improving postural performance to prevent injuries.

6 HYPOTHESES AND THE PURPOSE OF THE STUDY

The purpose of this study is to evaluate the effects of the ski boot on knee rotational moments in perturbation compared to the barefoot condition. The topic is important as a lot of medical studies have analysed the relevance of well-adjusted bindings of the common injuries of the knee joint ligaments, but the influence for example of the flexibility of the ski boot and the injury pattern has been neglected (Bürkner et al. 2008). According to Bürkner et al. (2008) further biomechanical studies examining the power transmission from ski boots to the lower leg, especially the rotational loads, are necessary. Despite highly developed ski bindings 62% of all lower leg fractures result from rotational trauma (Bürkner et al. 2008). Also, according to Noé et al. (2009) future research should include kinematic and kinetic analysis to gain understanding how efforts around the joints are involved in postural maintenance with external devices that generate ankle mechanical restrictions such as ski boots.

The effect of the ski boots during balance perturbations have not been investigated to the author’s knowledge. Possible cases that could happen during balance perturbations when wearing ski boots could be for example that the ski boot limits or even eliminates the muscles around ankle and shin which changes the postural control strategy. This could result a compensation in the knees, hip, and upper body, which could in turn increase the rotational moments in the knee. To examine this, we decided to study the rotation moments, the adduction moments, and the flexion angles of the knee during the balance perturbations.

We hypothesize that:

(H1) Rotation moments in the knee will be higher compared to barefoot condition, since ski boots cause significant valgus and external rotation misalignment of the knee, which may increase the risk of ACL injury. (Chaudhari & Andricchi 2006; Böhm & Senner 2008) In most cases, in alpine ski racing, the ACL injuries happen as a result of the external rotation of the tibia, which forces the knee into an extreme valgus position (Bere et al. 2011; Dai et al. 2012; Ettlinger et al. 1995; Hame et al. 2002; Stasi et al. 2013; Yukio et al. 2002). The ski boots also have their own role in falls and balance losses during skiing. As the skier falls back, the boot cuff is not free to rotate, and the rear spoiler resists the natural motion of the shank. This causes a resultant anterior shear force at the tibial plateau as the upper body and thigh tend to rotate in the opposite direction. This same mechanism happens when the skier lands from a jump in a rear weighted position or when the rear of the skis hit the slope first. The skis tend to rotate down so that they lay flat on the surface while the upper body resists to move. If the lower leg is forced to rotate with the ski, the ACL will be strained and often also injured. This mechanism is called the ”boot induced” injury. (Benoit et al. 2005) The ski boot does clearly cause misalignment and it might also be speculated that this causes extra pressure on the muscles around the knee and possibly increases muscle imbalance and patella grinding (Lann vel Lace & Błażkiewicz 2021).

(H2) The adduction moment in the knee differs from the barefoot condition, because according to Lann vel Lace and Błażkiewicz (2021) ski boots cause changes in the ranges of angles in the lower limb joints and increase muscle torques in the knee and hip joints. Also as already mentioned in H1 the adduction moments in the knee will be higher compared to barefoot condition, since ski boots cause significant valgus and external rotation misalignment of the knee. (Chaudhari & Andricchi 2006; Böhm & Senner 2008)

(H3) The flexion angle will be different when wearing ski boots compared to barefoot condition, because according to Lann vel Lace and Błażkiewicz (2021) ski boots cause changes in the ranges of angles in the lower limb joints. The flexion angle of the knee has an explanatory factor in knee injuries, because according to Hame et al. (2002) a fully extended or fully flexed knee represents the most dangerous loading conditions for knee injury from twisting accidents during skiing and at the time of a fall or loss of balance, the knee can be exposed to three different stresses according to Yukio et al. (2002): (1) an external rotation stress, which is forcing the knee into an extreme valgus position, (2) a stress that forces the knee to a hyperextension, or (3) a stress which is forcing the lower leg to internally rotate.

7 METHODS

This data was collected in a broader research in a collaboration with University of Jyväskylä and University of Eastern Finland and the data collection was performed at the HUMEA (Human Measurement and Analysis) laboratory at the Department of Applied Physics and Biomedicine of the University of Eastern Finland autumn 2022. The measurements were conducted before the competition season. Voluntary participants signed an informed consent as required by the Helsinki Declaration and the local ethics committee.

7.1 Subjects

Seventeen healthy (11 men, 6 women), national level alpine skiers (age 16.8 ± 2.1 yr, height 173.1 ± 10,6 cm, weight 68.4 ± 14.1 kg) were recruited in cooperation with Kuopio Region Sports Academy from the local alpine ski gymnasium and the local ski club. The inclusion criteria were the age of 14–20 and being an active alpine ski racer. Athletes with diseases or medication affecting the neuromuscular system, athletes with acute injury in lower limbs and athletes who have had a lower limb surgery or bone fracture in the past year were excluded from the study. The subjects were wearing their own ski boots during the measurements (ski boot flex index 90-170, canting 0,0–0,5 out (lateral) (five 0,5° and twelve 0,0). After comprehensive verbal and written explanations of the study, all subjects gave their written informed consent to participate. The participants also had the possibility to quit their participation at any moment.

7.2 Measurement protocol

The protocol was conducted at the HUMEA laboratory in Kuopio, Finland. The laboratory was equipped with reflective marker-based 3D motion capture system (100 Hz, Vicon Vero, Vicon Motion Systems Ltd., Oxford, United Kingdom) with 10 cameras, an instrumented treadmill (1,000 Hz, M-gait, Motek Medical, Houten, The Netherlands). Kinetic and kinematic data was analyzed. The capture volume was identified as the capture area and calibrated according to the manufacturer instructions using the Vicon T calibration wand prior to each trial. The calibration was repeated if the measured data was unacceptable.

The subject was informed of the proceedings of the study. After that the subject's height, weight, inter ASIS distance (the distance between the most anterior points of the left and right anterior superior iliac spine as measured in the coronal plane), ankle- and knee width was measured, also the dominant leg was asked (With which leg do you kick a football?). The subjects performed their own warm-up protocol (e.g., dynamic stretches, squats etc.). The preparations started with putting the reflective markers on the subject's body and the subject's own ski boots. The conventional gait model 2 (CGM2) marker set was used (figure 5), which is an open-sourced biomechanical model developed in Python 2. Additionally, 4 reflective markers were placed on the moving platform to capture the movement.

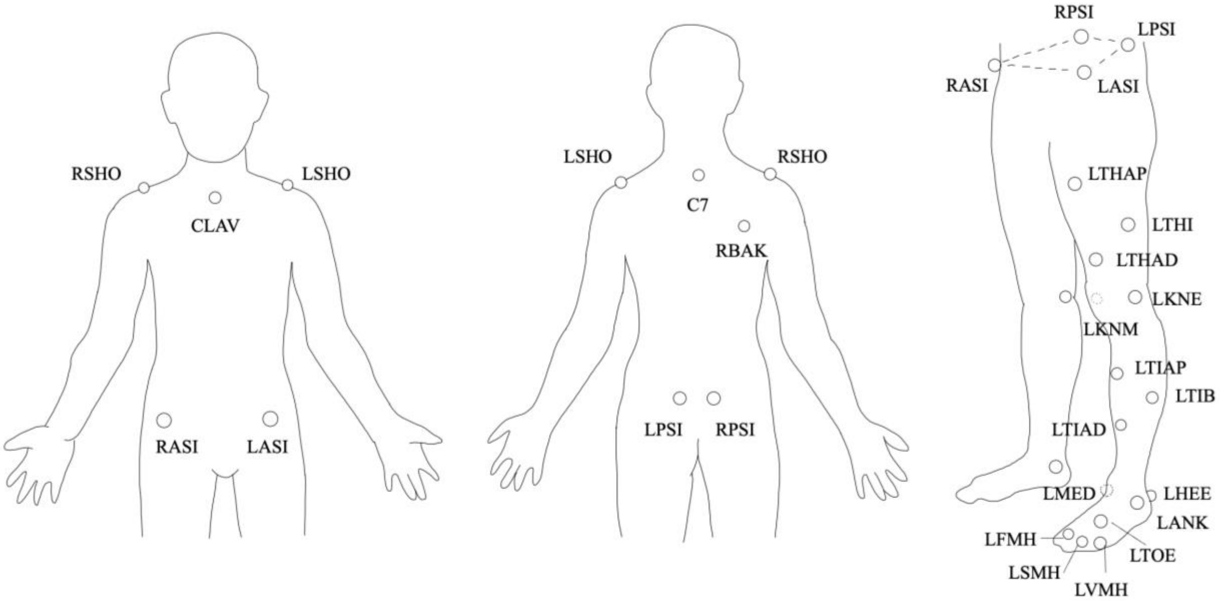


FIGURE 5. Used marker set (Referring to Peters et al. 2009)

Before the actual measurements the subject underwent a static calibration trial (standing still for a few seconds while being recorded). The measurements started with one barefoot practice trial followed by the actual measurement where the subject was standing on one leg with a slightly flexed leg (figure 6) on the instrumented treadmill (M-gait, Motek Medical, Houten, The Netherlands). The protocol included 10 perturbations with a given direction (first anterior-posterior (moving in posterior direction), second medial-lateral (moving in lateral direction), and lastly lateral-medial (moving in medial direction)) and speed (slow or fast) at random intervals (figure 7). The slow protocols were conducted in the medial-lateral and lateral-medial directions lasted in total, 48–49 s, and the fast protocol which was conducted in anterior-posterior direction only, lasted 52–53 s. The delay between perturbations was 4.5 ± 0.9s. In slow perturbations, the belt was set to move with a maximal acceleration (and deacceleration) of 0.3 m/s^2 targeting 0.15 m/s belt velocity for 0.5 s (belt movement ≈ 75 mm). For fast perturbations, the target speed was set to 0.25 m/s for 0.5 s, (belt movement ≈ 125 mm) while the maximal acceleration was limited to 4 m/s^2 and then decelerated to a full stop with the same acceleration. However, the treadmill was not able to reach the programmed 4 m/s^2 acceleration, reaching only about 75% of it. (Lesch et al. 2021)

FIGURE 6. Anterior-posterior trial wearing ski boots.

Participants were instructed to maintain balance as much as possible during all trials. The subject was wearing a harness for safety aspects in all perturbation trails. The foot touches were observed and counted. The same perturbation trial was done wearing ski boots after the barefoot trial. No practice trials were conducted in the ski boot trial.

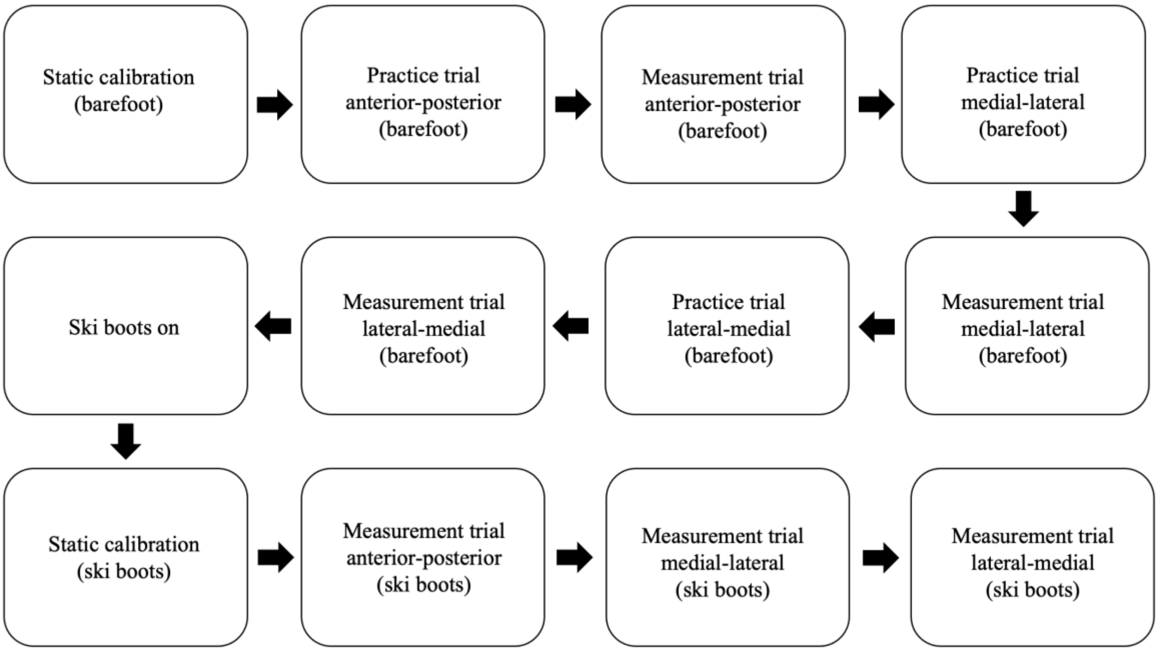


FIGURE 7. The measurement protocol.

7.3 Data analysis

Vicon Nexus software was used to compute the 3D trajectories of the reflective markers within the capture volume. The markers were identified manually, and gaps were filled within the Vicon Nexus software. Possible missing markers were extrapolated using MATLAB (Mathworks Ltd. Massachusetts, United States). The CGM2 marker set was used, however due to some problems with the analysis, the Plug in Gait (PiG) model was chosen. It was possible to use PiG, because both models use the same markers even if CGM2 uses more markers. Using the PiG modeling is faster and made it possible to analyze the data more efficiently. Marker data were filtered using a fourth-order zero-lag 6 Hz low-pass Butterworth filter. The data (knee rotational moments, adduction moments and flexion angles) were processed and analyzed with custom-made scripts written in MATLAB.

The mean values of the 10 perturbations per direction (posterior, lateral, medial) were calculated. The absolute maximal rotation moment, adduction moment and flexion angle and the absolute maximal change to 150 ms were calculated. Also, the effect of the ski boot's canting angle was analyzed. The 150 ms time window was chosen based on the earlier studies which noted that noncontact ACL injuries are expected to occur between 0 and 61 milliseconds after initial contact according to Bates et al. (2020) and at 47 to 98 milliseconds after initial contact according to Ueno et al. (2021). The 150 ms time window made it also possible to measure before the belt started to deaccelerate (500 ms) and before possible foot touches with the other leg were conducted. The trials where the other foot was clearly touching the ground, the markers were "jumping", or the measurement had a poor quality were excluded from the study.

The moments are reported in Newton meters (Nm) and the flexion angles in degrees (°). Negative values in knee rotational moments state for external rotation (lateral rotation) and positive values for internal rotation (medial rotation). In knee adduction moments the negative value state for abduction whereas positive values state for adduction. In knee flexion angles a bigger value states for flexion angle and negative values state for extension. The absolute maximum and change value can therefore be either positive or negative.

7.4 Statistics

The mean values of the 10 perturbations were calculated in MATLAB (Mathworks Ltd. Massachusetts, United States). The absolute maximal rotation moment, adduction moment and flexion angle and the absolute maximal change from the start position to 150 ms were calculated from the mean values of the 10 perturbations using Microsoft Excel 2020 (Microsoft Corporation, Washington, United States). The means and standard deviations were calculated from the maximal values and change values. The means of the maximal values and change values of barefoot and ski boot conditions were compared. The statistical analyses were conducted using IBM SPSS Statistic 28 (IBM Corp., New York, United States). The normality of the data was analyzed using the Shapiro-Wilk test. Based on the normally distributed data the two-sided paired sample T-test was chosen to compare the means of the barefoot trials and ski boot trials. The effect of the ski boot canting angle (0.00°/0.05°) was tested with the two-sided independent sample T-test, after the variance was tested with the Levene's test. The statistical significance was set at $p < 0.05$.

8 RESULTS

In this study the maximum value states more for the effect of the ski boot on the knee position, while the change value states more for the effect of the ski boot on balance. The means and standard deviations were calculated from the maximal values and change values. Next the means of the maximal values and change values of barefoot and ski boot conditions were compared, the results are shown in tables in the following sub paragraphs. The moments are reported in Newton meters (Nm) and the flexion angles in degrees (°).

Even if the time window for this research was set for 150 ms, it must be noted that the knee rotational moments and knee adduction moments continued to increase (or decrease) in some cases even after the selected time window (figures 8 and 9) until the deacceleration phase of the treadmill mat (500 ms). The flexion angles of the knee were relatively constant the whole perturbation (figure 10).

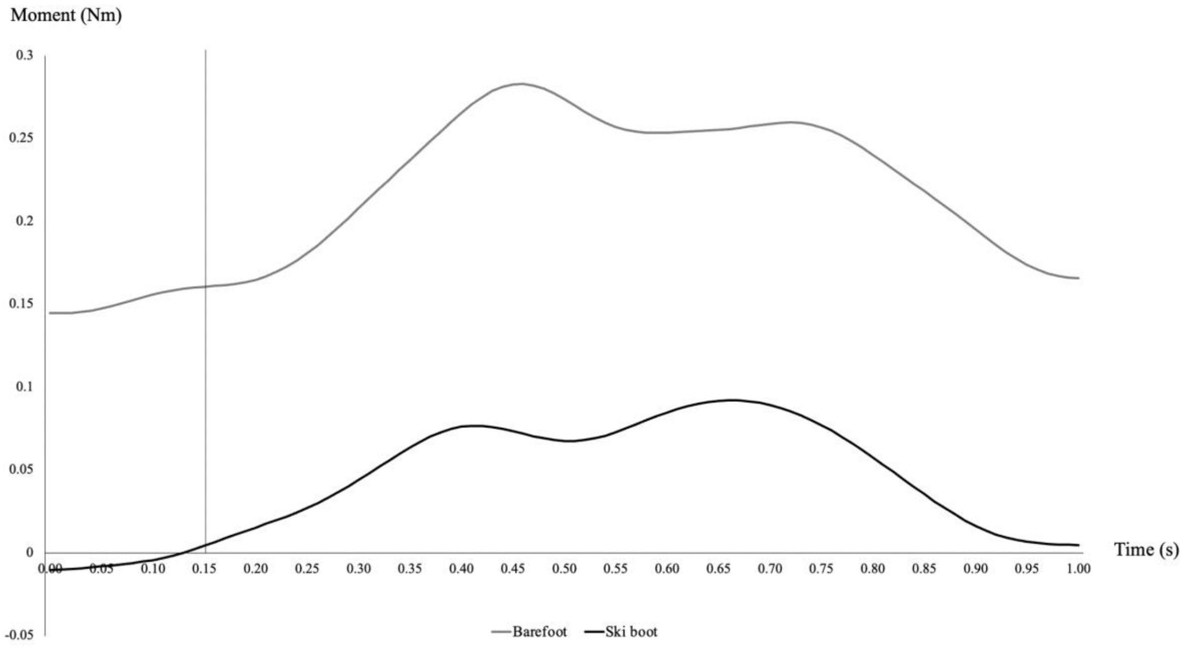


FIGURE 8. Subject's nr. 10 knee rotation moments in lateral perturbation barefoot vs. wearing ski boots (vertical line shows the 150 ms time window).

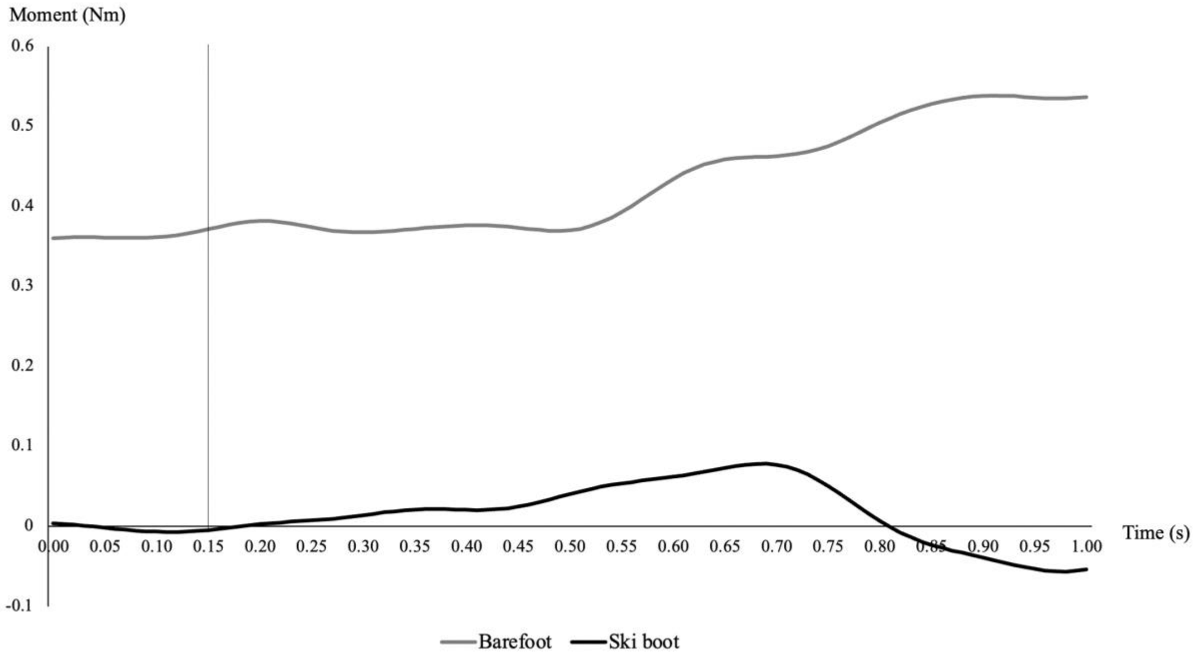


FIGURE 9. Subject's nr. 2 knee adduction moments in lateral perturbation barefoot vs. wearing ski boots (vertical line shows the 150 ms time window).

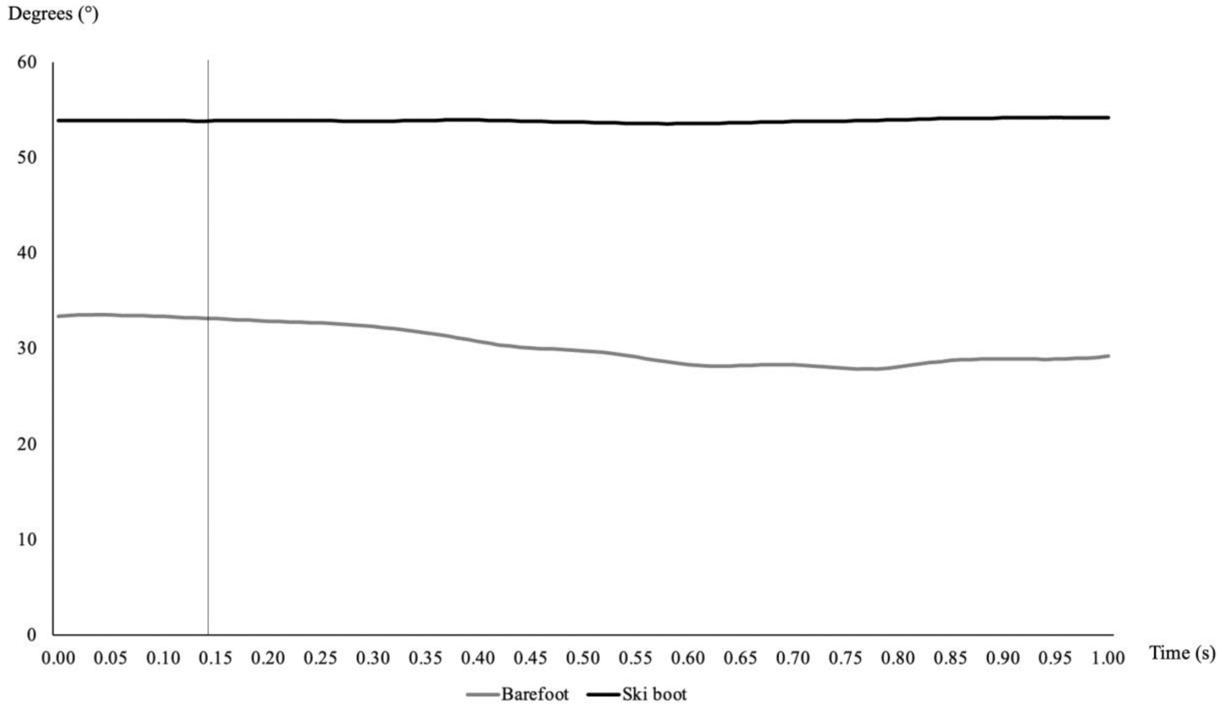
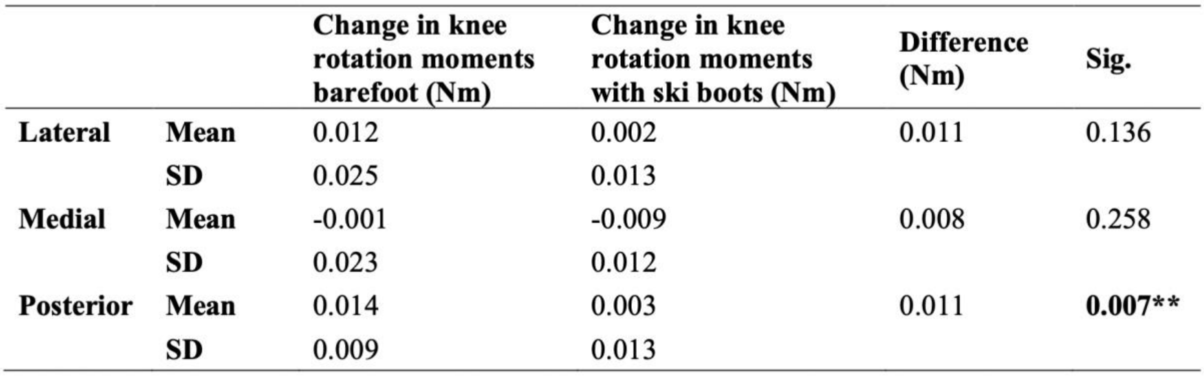


FIGURE 10. Subject's nr. 3 knee flexion angles in lateral perturbation barefoot vs. wearing ski boots (vertical line shows the 150 ms time window).

8.1 Knee rotation moments

Statistically significant differences in knee rotation moments between the barefoot and ski boot conditions were found only in the maximal change in posterior perturbation (difference = 0.011 Nm, p = 0.007) (table 3). No differences were found in the maximal knee rotation moments between the barefoot and ski boot conditions (table 4). The knee rotation moments between the barefoot and ski boots condition in posterior perturbation can be seen in figure 11, where the knee is closer to a neutral position (closer to 0) barefoot than when wearing ski boots. However, the rotation moments in the barefoot condition are increasing faster and more. The same effect can be seen in figure 12, where the knee rotation moments in medial perturbation are increasing more and faster for the barefoot condition that for the ski boot condition. The rotation moments are also negative for the ski boot condition but more constant that in the barefoot condition.

TABLE 3. Maximal changes in knee rotation moments barefoot vs. wearing ski boots.
$^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$



		Change in knee rotation moments barefoot (Nm)	Change in knee rotation moments with ski boots (Nm)	Difference (Nm)	Sig.
Lateral	**Mean**	0.012	0.002	0.011	0.136
	SD	0.025	0.013		
Medial	**Mean**	-0.001	-0.009	0.008	0.258
	SD	0.023	0.012		
Posterior	**Mean**	0.014	0.003	0.011	**0.007****
	SD	0.009	0.013		

TABLE 4. Maximal knee rotation moments barefoot vs. wearing ski boots.
$*p < 0.05$; $**p < 0.01$; $***p < 0.001$

		Maximal knee rotation moments barefoot (Nm)	**Maximal knee rotation moments with ski boots (Nm)**	**Difference (Nm)**	**Sig.**
Lateral	**Mean**	0.016	-0.017	0.033	0.184
	SD	0.052	0.093		
Medial	**Mean**	0.095	0.091	0.004	0.840
	SD	0.045	0.085		
Posterior	**Mean**	0.022	0.017	0.004	0.700
	SD	0.049	0.079		

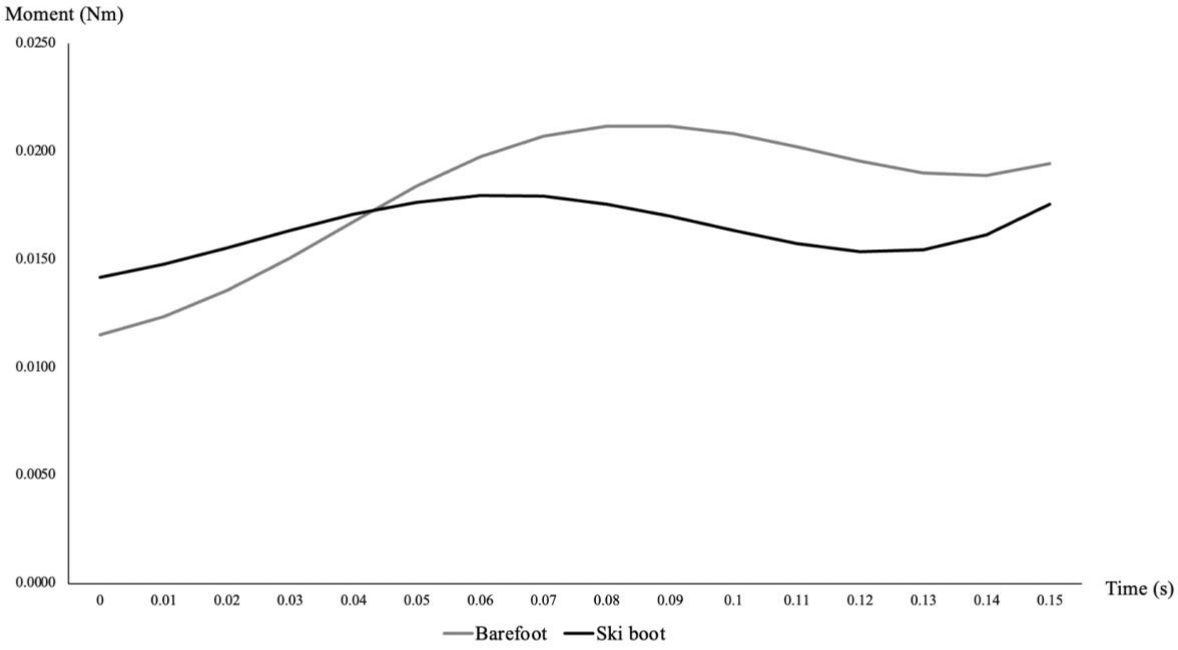


FIGURE 11. Mean knee rotation moments barefoot vs. wearing ski boots (posterior perturbation).

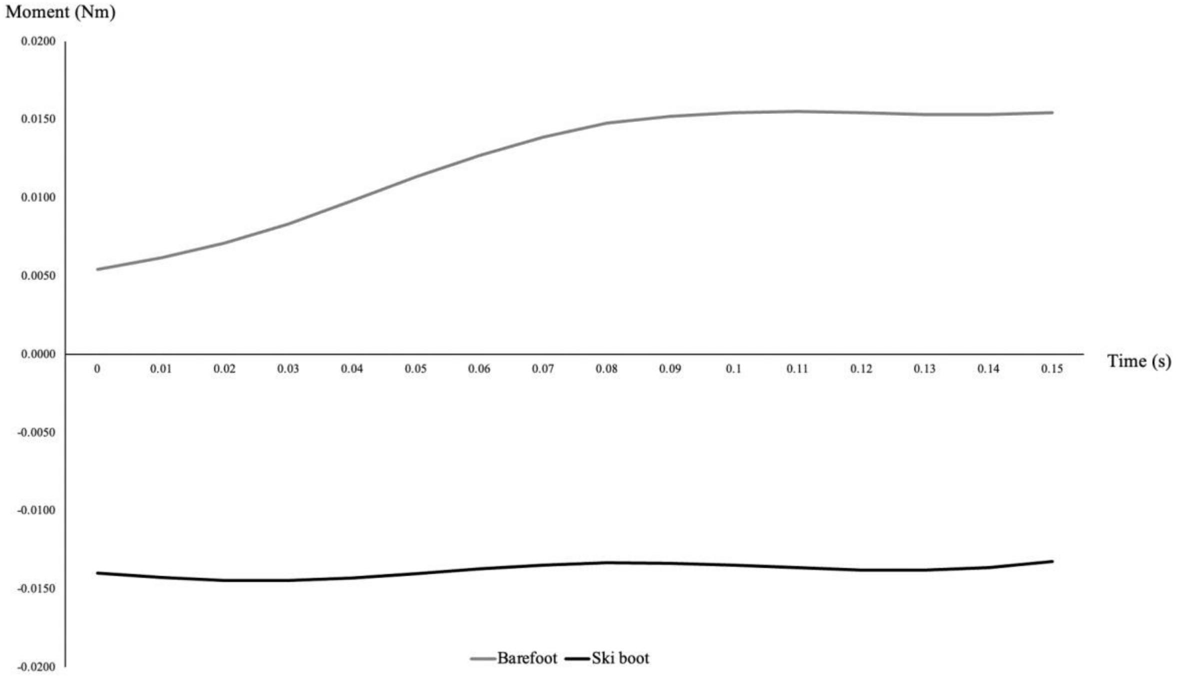


FIGURE 12. Mean knee rotation moments barefoot vs. wearing ski boots (medial perturbation)

8.2 Knee adduction moments

The differences in maximal knee adduction moments were statistically significant in every perturbation direction as shown in table 5. The difference for barefoot and ski boot condition for lateral perturbation was 0.250 Nm ($p = 0.002$), for medial perturbation 0.193 Nm ($p = 0.003$), and 0.291 Nm ($p < 0.001$) for posterior perturbation. No statistically significant differences were found in the maximal change values between the barefoot and ski boot conditions as shown in table 6. The almost non-existent change of the values can also be seen in figures 13, 14 and 15. The differences between the maximal values can also be seen in figures 13, 14 and 15, where the adduction moments are higher for the barefoot condition in every perturbation direction.

TABLE 5. Maximal knee adduction moments barefoot vs. wearing ski boots. *p < 0.05; **p < 0.01; ***p < 0.001

		Maximal knee adduction moments barefoot (Nm)	**Maximal knee adduction moments with ski boots (Nm)**	**Difference (Nm)**	**Sig.**
Lateral	**Mean**	0.473	0.223	0.250	**0.002****
	SD	0.255	0.147		
Medial	**Mean**	0.533	0.340	0.193	**0.003****
	SD	0.203	0.151		
Posterior	**Mean**	0.615	0.324	0.291	**<0.001*****
	SD	0.219	0.136		

TABLE 6. Maximal changes in knee adduction moments barefoot vs. wearing ski boots. *p < 0.05; **p < 0.01; ***p < 0.001

		Change in knee adduction moments barefoot (Nm)	**Change in knee adduction moments with ski boots (Nm)**	**Difference (Nm)**	**Sig.**
Lateral	**Mean**	0.003	0.012	-0.009	0.589
	SD	0.067	0.009		
Medial	**Mean**	-0.006	-0.007	0.001	0.987
	SD	0.046	0.016		
Posterior	**Mean**	-0.044	-0.036	-0.008	0.460
	SD	0.033	0.017		

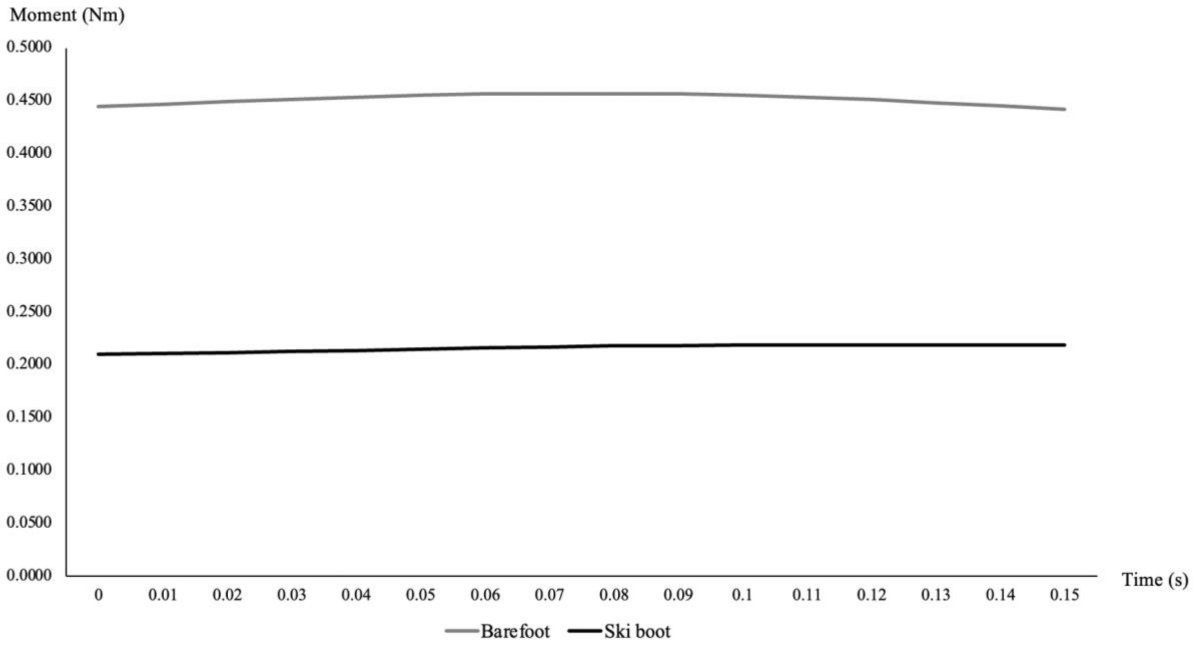


FIGURE 13. Mean knee adduction moments barefoot vs. wearing ski boots (lateral perturbation).

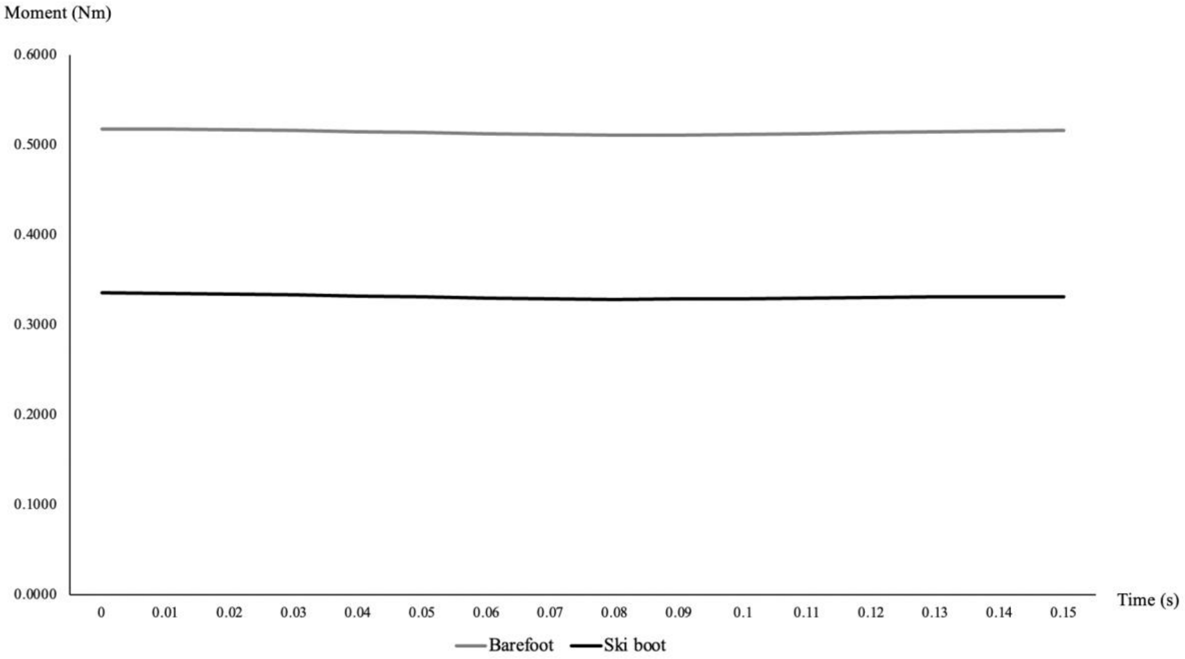


FIGURE 14. Mean knee adduction moments barefoot vs. wearing ski boots (medial perturbation).

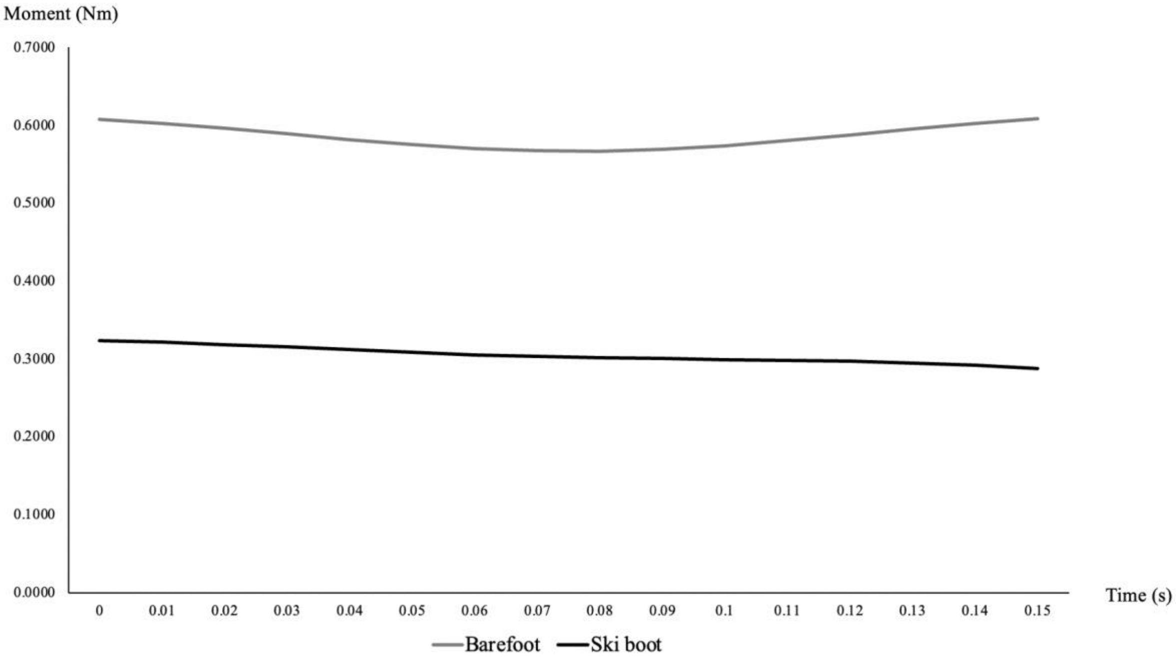


FIGURE 15. Mean knee adduction moments barefoot vs. wearing ski boots (posterior perturbation).

8.3 Knee flexion angles

Statistically significant differences in maximal knee flexion angles were found in all perturbation directions as shown in table 7. The difference for barefoot and ski boot condition for lateral perturbation was -7.4° ($p = 0.005$), for medial perturbation -11.5° ($p < 0.001$), and -7.5° ($p = 0.013$) for posterior perturbation, which means that the knee was more flexed when wearing ski boots. Statistically significant differences were also found in the maximal changes in the knee flexion angles in posterior perturbation direction, where the difference between the barefoot condition and ski boot condition was 0.99° ($p < 0.001$) (table 8). In posterior perturbation direction, the knee was extended more towards the end when wearing ski boots compared to the barefoot condition (figure 16). In medial and lateral perturbation directions the changes were small and almost constant as seen in figures 17 and 18.

TABLE 7. Maximal knee flexion angles barefoot vs. wearing ski boots.

*p < 0.05; **p < 0.01; ***p < 0.001

		Maximal knee flexion angles barefoot (°)	**Maximal knee flexion angles with ski boots (°)**	**Difference (°)**	**Sig.**
Lateral	**Mean**	34.8	42.2	-7.4	**0.005****
	SD	10.0	13.1		
Medial	**Mean**	32.3	43.8	-11.5	**<0.001*****
	SD	11.3	7.1		
Posterior	**Mean**	35.8	43.3	-7.5	**0.013***
	SD	10.6	7.8		

TABLE 8. Maximal changes in knee flexion angles barefoot vs. wearing ski boots.

*p < 0.05; **p < 0.01; ***p < 0.001

		Change in knee flexion angles barefoot (°)	**Change in knee flexion angles with ski boots (°)**	**Difference (°)**	**Sig.**
Lateral	**Mean**	-0.05	0.03	-0.08	0.341
	SD	0.33	0.10		
Medial	**Mean**	0.12	-0.01	0.13	0.077
	SD	0.31	0.10		
Posterior	**Mean**	0.39	-0.60	0.99	**<0.001*****
	SD	0.24	0.24		

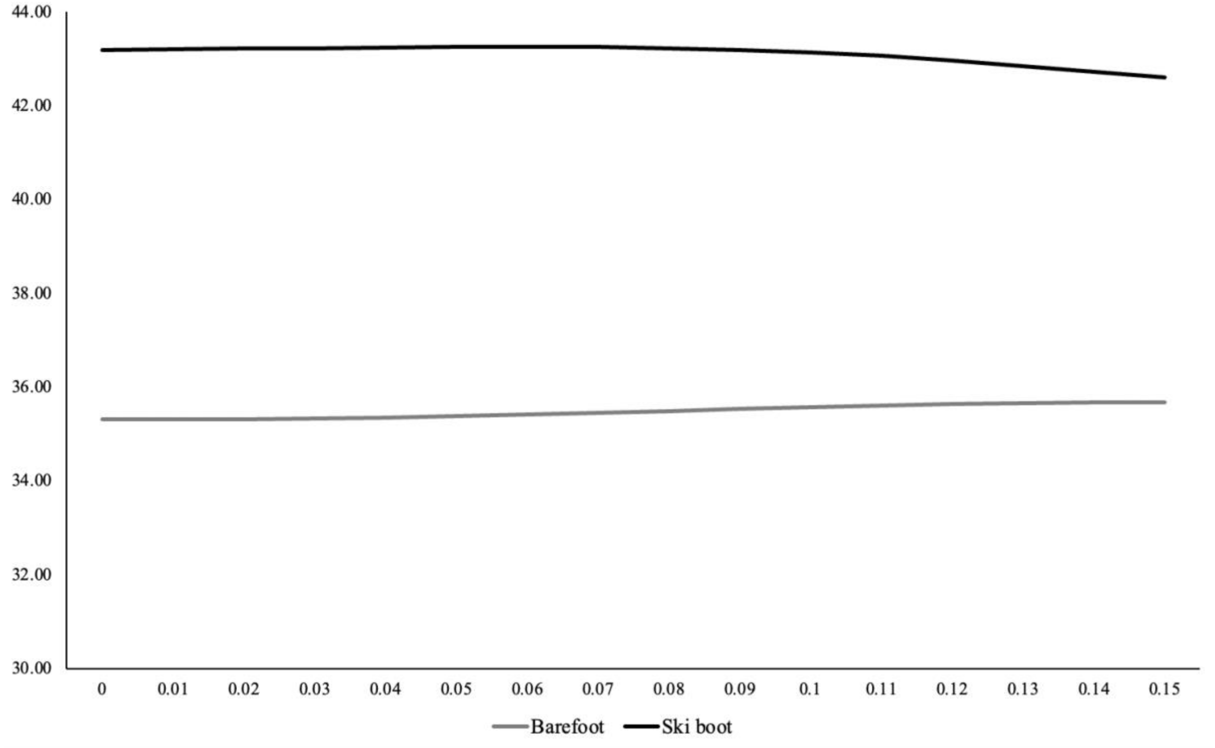


FIGURE 16. Mean knee flexion angles barefoot vs. wearing ski boots (posterior perturbation).

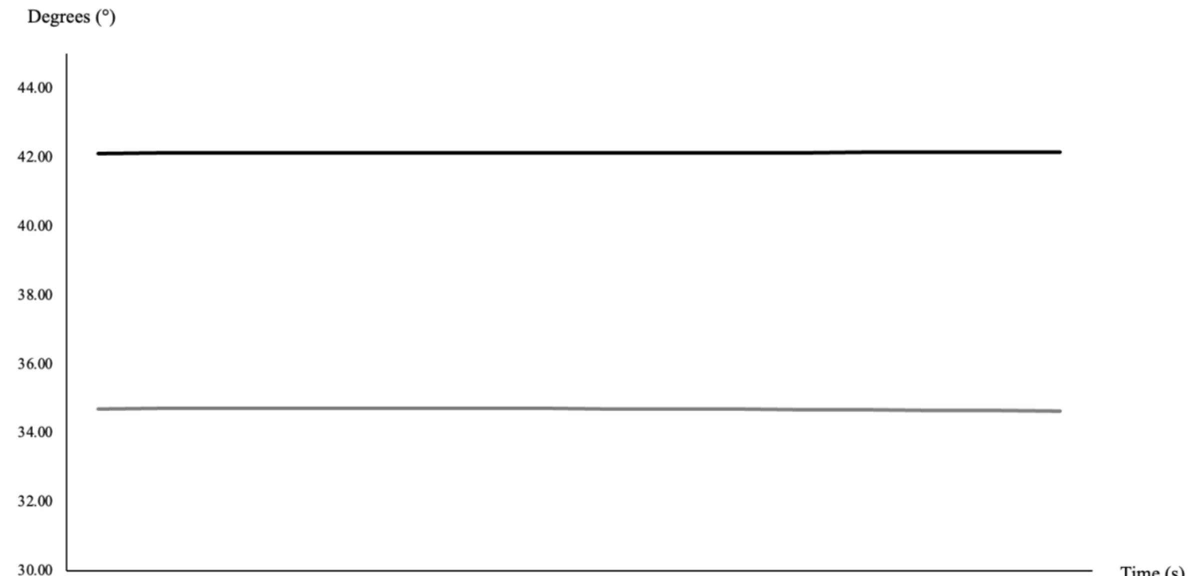


FIGURE 17. Mean knee flexion angles barefoot vs. wearing ski boots (lateral perturbation).

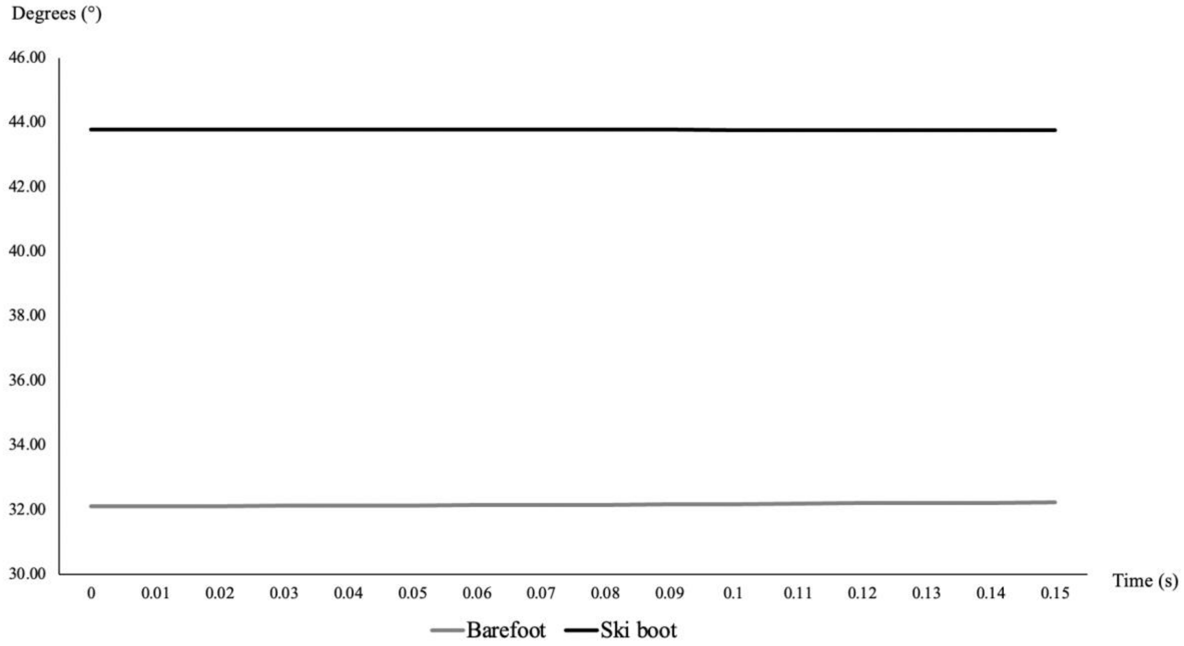


FIGURE 18. Mean knee flexion angles barefoot vs. wearing ski boots (medial perturbation).

9 DISCUSSION

The main purpose of this study was to examine the acute response of the rotational moments in the knees, when wearing ski boots during a simulated balance perturbation. In addition to examining the acute response of the rotational moments, the purpose of this study was to examine the knee adduction moments and knee flexion angles.

We hypothesized that (H1) The rotation moments in the knee will be higher compared to barefoot condition, since ski boots cause significant external rotation misalignment of the knee, which may increase the risk of ACL injury. (Chaudhari & Andricchi 2006; Böhm & Senner 2008) (H2) The adduction moment in the knee differs from the barefoot condition, because according to Lann vel Lace and Błażkiewicz (2021), ski boots cause changes in the ranges of angles in the lower limb joints and increase muscle torques in the knee and hip joints. The adduction moments in the knee will also be higher compared to barefoot condition since ski boots cause significant valgus misalignment of the knee. (Chaudhari & Andricchi 2006; Böhm & Senner 2008) (H3) The flexion angle of the knee has an explanatory factor in knee injuries, because according to Hame et al. (2002) a fully extended or fully flexed knee represents the most dangerous loading conditions for knee injury from twisting accidents during skiing and at the time of a fall or loss of balance.

9.1 Main findings

The main findings of this study were that the ski boot had almost no effect on the knee rotation moments in perturbation. Statistically significant differences in knee rotation moments between the barefoot and ski boot conditions were found only in the maximal change in posterior perturbation (difference = 0.011 Nm, $p = 0.007$). However, the ski boot had an effect on the knee adduction moments, but not the way we hypothesized, as the knee adduction moments were higher for the barefoot condition than for the ski boot condition in every perturbation direction. The differences in maximal knee adduction moments were statistically significant in every perturbation direction. The difference for barefoot and ski boot condition for lateral perturbation was 0.250 Nm ($p = 0.002$), for medial perturbation 0.193 Nm ($p = 0.003$), and 0.291 Nm ($p < 0.001$) for the posterior perturbation. No statistically significant differences in knee adduction moments were found in the maximal change values between the barefoot and ski boot conditions.

The ski boot affected the knee flexion angle as expected, but not as drastically as it was expected. Statistically significant differences in maximal knee flexion angles were found in all perturbation directions. The difference for barefoot and ski boot condition for lateral perturbation was -7.4° (p = 0.005), for medial perturbation -11.5° (p < 0.001), and -7.5° (p = 0.013) for posterior perturbation. Statistically significant differences were found also in the maximal changes in the knee flexion angles in posterior perturbation direction, where the difference between the barefoot condition and ski boot condition was 0.99° (p < 0.001). The ski boot pushes the knee forward, which increases the flexion angle.

The effect of the ski boot canting angle on the rotation moments, adduction moments and the flexion angle were also tested, in order to possibly get explanatory results. The ski boot canting angle had no statistically significant effect on the knee rotational moments, knee adduction moments or the knee flexion angles. Thus, it must be noted that there were only five subjects using ski boots with a 0.05° outward canting, which could mean that the sample size was probably too small. The biggest differences which were found were the mean value for maximal knee rotation moments (posterior perturbation) where the mean was -0.285 Nm (SD 0.058) for 0.5° angle group and 0.38 Nm (SD 0.081) for the 0.00° angle group (effect size (Cohen's d) 0.886). The difference could indicate that even small changes in the canting angle have an effect on at least the rotation moments.

9.1.1 Knee rotation moments

Statistically significant differences in knee rotation moments between the barefoot and ski boot conditions were found only in the maximal change in posterior perturbation (difference = 0.011 Nm, p = 0.007) (table 4). No differences were found in the maximal knee rotation moments between the barefoot and ski boot conditions. Even if the differences were small and not statistically significant, the effect of the ski boot can be seen for example in figure 12, where the rotation moments are negative for the ski boot condition and positive for the barefoot condition. This means that the ski boot pushes the knee in an external rotation, which has been confirmed in earlier studies (Chaudhari & Andricchi 2006; Böhm & Senner 2008; Lann vel Lace and Błazkiewicz 2021). The ski boot seems also to give a bigger support base, since the rotation moments are more constant in the ski boot condition that in the barefoot condition. This has been demonstrated in for example Pai and Patton's (1997) study, where the increased length of the support base caused by the ski boot cuff facilitated the maintenance of standing posture and decreased the amplitude of postural sways. Also, in Noé's et al. (2007) study the results revealed that the mechanical effects due to wearing ski boots did not affect the postural balance, in fact the COP area was even smaller when wearing ski boots in the standing posture compared to standing posture without ski boots.

The time window for this research was set for 150 ms, but it must be noted that the knee rotational moments continued to increase (or decrease) in some cases even after the selected time window (figure 8) until the deacceleration phase of the treadmill mat (500 ms). This often happens, due to inertia. The velocity of the mass accelerates slowly and deaccelerates slowly, which is why the body tend to move until another force (deacceleration) is affecting the body. The 150 ms time window was chosen based on the earlier studies which noted that noncontact ACL injuries are expected to occur between 0 and 61 milliseconds after initial contact, when the moments are at their biggest, according to Bates et al. (2020) and at 47 to 98 milliseconds after initial contact according to Ueno et al. (2021). The time after 150 ms was not taken under consideration, as the main purpose of this study was to examine the acute response of the rotational moments in the knees when wearing ski boots during a simulated balance perturbation. With the acute response we were aiming to concentrate on the possible injury time window. Thus, it must be noted that the forces caused by the perturbation were really small and were not meant to cause any injuries or injury risks.

Rotation moments in alpine skiing have been reported for example in Klous et al. (2014) study, where the rotation moments increased up to 1.3 ± 0.3 Nm in the completion phase of a carving turn (radius ≈ 17 m). Other knee moments have been reported for example in Heinrich's et al. (2022) study, where the highest joint moments at the outside leg during a carving turn (radius + 16 m, speed minimum 14 m/s) where found in knee extension moment with 1.02 Nm/kg. The highest rotation moments observed this study was 0.091 Nm (maximal rotation moment when wearing ski boots in medial perturbation), which is 7% of the moments observed in Klous' et al. (2014) study. The percentage is small, but it could indicate the patterns happening if the forces would have been bigger or the perturbations would have been stronger.

The ski boot canting angle had no statistically significant effect on the knee rotational moments. Anyway, the position of the ski boot is important since many skiers tend to have valgus or varus leg alignments (Colonna et al. 2013). One solution to overcome the problem of the knee posture is the canting mechanism, which allows medial and lateral tilting of the cuff respective to the base of the boot. (Böhm & Senner 2008; Colonna et al. 2013; Senner et al. 2013; Wilson et al. 2021) The subjects in this study were using either a ski boot with a 0.05° lateral canting or a "neutral" 0.00° ski boot. The lateral canting makes the ski boot feel more "aggressive", while the medial canting can significantly decrease for example knee valgus, improve some postural control measures which are associated with balance quality, and reduce the activation levels of the Vastus Lateralis, Tibialis Anterior and Biceps Femoris muscles, which makes the balancing easier. (Wilson et al. 2021). This suggests that the lateral canting does not at least reduce the external rotation or knee valgus, as might be seen from the results.

9.1.2 Knee adduction moments

The differences in maximal knee adduction moments were statistically significant in every perturbation direction. No statistically significant differences were found in the maximal change values between the barefoot and ski boot conditions. The ski boot had an effect on the knee adduction moments, but not the way we hypothesized, as the knee adduction moments were higher for the barefoot condition than for the ski boot condition in every perturbation direction. The adduction moments for the ski boot condition were also more constant than for the barefoot condition. An explanation to this could be the same than for the rotational moments. The ski boot seems to give a bigger support base, since the adduction moments are more constant in the ski boot condition that in the barefoot condition. This has been demonstrated in for example Pai and Patton's (1997) study, where the increased length of the support base caused by the ski boot cuff facilitated the maintenance of standing posture and decreased the amplitude of postural sways. Also, in Noé's et al. (2007) study the results revealed that the mechanical effects due to wearing ski boots did not affect the postural balance, in fact the COP area was even smaller when wearing ski boots in the standing posture compared to standing posture without ski boots.

Based on the earlier studies we hypothesized that the maximal adduction moments would be bigger for the ski boot condition than for the barefoot condition, as it has been demonstrated that ski boots cause changes in the ranges of angles in the lower limb joints and increase muscle torques in the knee and hip joints (Lann vel Lace and Błaźkiewicz 2021) and that ski boots cause significant valgus and external rotation misalignment of the knee. (Chaudhari & Andricchi 2006; Böhm & Senner 2008) An explanation to that this did not happen could be that when wearing the ski boots, the knee was in a more flexed position. When the knee is in a more flexed position, the COM is lower. When the COM is lower, the force vector is shorter. This in turn affects the moments in a reducing pattern. That is to say, that the adduction moments could be smaller in the ski boot condition due to the fact that the knee flexion angle was bigger in the ski boot condition than in the barefoot condition.

Another explanation to that this did not happen, could be that the increased length of the support base was more beneficial in this kind of test, where the forces were small and the changes almost constant due to that. It could also be possible that when the ankle was supported by the ski boot, the upper body and hip had a bigger role in keeping the balance and resulted the ankle and knee to stay at a constant position. As noted before ski boots can improve lateral balance because they restrict ankle inversion and eversion but at the same time limit anterior and posterior control strategies by reducing dorsiflexion (Noé et al. 2018B).

The time window for this research was set for 150 ms, but it must be noted that also the knee adduction moments continued to increase (or decrease) in some cases even after the selected time window (figure 9) until the deacceleration phase of the treadmill mat (500 ms).

9.1.3 Knee flexion angles

Statistically significant differences in maximal knee flexion angles were found in all perturbation directions. The difference for barefoot and ski boot condition for lateral perturbation was -7.4° ($p = 0.005$), for medial perturbation -11.5° ($p < 0.001$), and -7.5° ($p = 0.013$) for the posterior perturbation, which means that the knee was more flexed when wearing ski boots. This result is kind of obvious, because the ski boot pushes the knee mechanically in a more flexed position. The knee flexion angle when wearing ski boot could be affected for example of the ski boot stiffness and forward angles, which were unknown in this study, as the ski boot stiffness do not have any standardized values. Most manufacturers report only their own ”flex index”, which is associated with the forward flexion stiffness of the ski boot. The ”flex index” definitions has not been standardized (ISO 5355; ISO 11088; Petrone et al. 2013; Reichel et al. 2008). The forward flexion angle could have been measured, but the small sample size would probably not have allowed to see any statistically significant differences.

Statistically significant difference was found also in the maximal changes in the knee flexion angles in posterior perturbation direction, where the difference between the barefoot condition and ski boot condition was 0.99° ($p < 0.001$), where the knee was extended more towards the end when wearing ski boots compared to the barefoot condition (figure 16). In medial and lateral perturbation directions the changes were small and almost constant. The need to extend the knee when moving backward could again be a result of inertia. The velocity of the mass accelerates slowly and deaccelerates slowly. The big mass wants to stay forward, which makes the knee to extend. The bigger flexion angle when wearing ski boots also allows a bigger possibility to change in the flexion angle. The same phenomenon happens when the skier moves from a steep part of the slope to a flatter part of the slope. For example, in Nakazato’s et al. (2001) study, COP moved in the front-back direction (anterior-posterior) at the steep part of the slope 271,7 mm and at the flat part 195,5 mm. A greater movement indicates a greater need to control balance (Falda-Buscaiot et al. 2017). When the slope is steep, more pressure is required on the front of the foot during the initiation phase, in order to make the turn start quickly. On a flat slope, the pressure is distributed more evenly under the foot, which usually happens because the skier concentrates more on gliding on the ski. (Falda-Buscaiot et al. 2017.) The velocity changes during skiing constantly because of i.e., the acceleration, due to inertia, the skier’s body tends to lean backward for positive accelerations and respectively lean forward for negative accelerations. (Lesnik et al. 2017) Also this could be used as an explanatory factor, when reviewing the reason for the changes in the knee flexion angles in posterior perturbation direction.

No fully extended or fully flexed knee positions were observed either in the barefoot nor ski boot conditions in this study. As noted in the hypotheses the flexion angle of the knee has an explanatory factor in knee injuries, because according to Hame et al. (2002) a fully extended or fully flexed knee represents the most dangerous loading conditions for knee injury from twisting accidents during skiing and at the time of a fall or loss of balance. The ski boot affects the knee by pushing it mechanically forward and puts the knee in a more flexed position as in the barefoot condition as earlier mentioned, but the ski boot did not cause any extreme positions in this study. Of course, if the perturbations would have been bigger (i.e. faster, with higher acceleration or bigger amplitude), the possible changes could have been bigger, and possibly affected the knee flexion angle increasingly (or decreasingly). Thus, it has to be noted that the flexion angle was relatively constant when wearing ski boots, possibly due to the increased support base (Pai and Patton 1997).

9.2 Limitations

A limitation of this study was the specific postural task, which was executed in the laboratory which is far from a typical real skiing situation. In real skiing the ski boots are attached to the skis and in fall or balance loss situation the long lever arm of the ski applies extreme torque to the knee. (Nusser et al. 2016; Brucker et al. 2014; Burtcher et al. 2008) Skiing is also affected by many other things such as the temperature, characteristics of the snow surface and need to perform technical movements. Also, the boot stiffness is different in real skiing because of the colder temperatures. (Petrone et al., 2013; Noé et al. 2018A).

Only the dominant leg was measured in this study. The choice can be explained by the fact that during skiing the pressure is distributed differently on both legs depending on the phase of the turn. For example, in Falda-Buscaiot's et al. (2017) study, the pressure distribution at the steering and completion phases, the pressure distribution was 75% on the outside leg and 25%

on the inside leg. Generating high pressure on one ski (i.e., the outer leg) is a basic requirement if you want to make the ski bend and turn more tightly than what the ski's turning radius indicates (Falda-Buscaiot et al. 2017). It has also been noted that all forces and moments on the knee joint loading are higher at the outer leg in all turn phases. (Klous et al. 2012). In addition to these, the most injured body part in alpine skiing is the outer knee (Urabe et al. 2002).

Knee adduction, rotation moments and flexion angles are challenging to evaluate with marker-based motion capture due to skin motion artifact and errors in knee marker placement. However, it has been noted that the results correlate highly with other measurement techniques and can therefore be counted as a valid method according to Li et al. (2012). To capture the movement even more precisely, a higher than 100 Hz capture frequency could have been used. The markers were also put separately on the ski boots. Therefore, the markers in the barefoot and ski boot trials might not have been on the exact same places. This could affect for example the knee angle measures.

The reliability of the protocol and of the mat movement of this study has been examined in Lesch's et al. (2021) research. The aims of Lesch's et al. (2021) study was to quantify the precision, accuracy, and reliability of the belt movement for delivering perturbations. The belt movement was highly repeatable. However, in the fast protocol, the belt reached only about 75% of the maximal allowed acceleration. The cause for this was the limitation in the rate of acceleration rise. Nonetheless, even though the maximal allowed acceleration set for this protocol was not reached, the peak accelerations remained highly consistent between the days and across participants, with a typical error of less than 0.5% of the mean in the fast protocol.

The short-term learning effect is also one limitation that must be taken into account when reviewing the study. In Lesch's et al. (2021) study where the reliability of the protocol and of the mat movement of this study was examined, the small sample limited the ability to detect short-term learning effects. Studies have found that there is a learning effect in balance responses to external perturbations, which can negatively impact reliability (Lysholm et al. 1998). Due to that the subjects performed the practice perturbation trials only before the barefoot measurement trials, but not before the ski boot measurement trials. However, when the subjects were performing the ski boot measurement trials, they had already executed a minimum of six perturbation trials before. Already the six perturbation trials could have a short-term learning effect.

The perturbations were conducted on an instrumented treadmill, which caused the subject to aways know the perturbation direction. This made it possible to anticipate the perturbation more easily. This might be a problem in pure dynamic balance measurements. However, in alpine skiing it is possible to anticipate the perturbation direction up to some limit. For example, when going from a steep part to a flat and vice versa or going over bumps or skiing on an inclined slope. Of course, it is impossible to anticipate every perturbation happening in skiing. The same could be said about the perturbation protocol used in this study, as the frequency of the perturbations was randomized.

The study had also a relatively small sample size, which could affect the result and the reliability. With a bigger sample size, it could have been possible to get bigger differences or more statistically significant results. The same applies to the forces, it must be noted that the forces caused by the perturbation were small and they were not meant to cause any injuries or injury risks, and therefore also the differences and maximum values where relatively small. At the same time, it must be noted that even if the sample size was relatively small, the subject group was close to homogeneous. The subjects were all recruited from the local ski gymnasium and the local ski club. The subjects were following a similar training pattern in both physical and technical training. In this age group (age 16.8 ± 2.1 yr) the training is not yet specified to one discipline, and it can be assumed that a very versatile training and competition program have been executed for all the athletes. The homogenous group can be seen to affect the reliability of the study in a positive way.

As the purpose of the study was to study the effects of the ski boot on moments affecting the knee, the ski boots could have been inspected more carefully. For example, the stiffness of the cuff, the angle of the boot cuff (anterior-posterior), cuff height etc. could have been measured. The best solution could have been to use the same ski boots for all or compare few types of ski boots among themselves. In this case it was not possible to use the same ski boots for everyone because of the size, shoe size, strength, and mass differences between the subjects. It is not optimal to compare the effects of the same ski boot for example on a 50 kg 15 years old girl and a 100 kg 18 years old boy.

Lastly the time window can be assumed to be a limitation of the study. The time window for this research was set for 150 ms, but it must be noted that the knee rotation moments and adduction moments continued to increase (or decrease) in some cases even after the selected time window until the deacceleration phase of the treadmill mat (500 ms). This often happens, due to inertia. The velocity of the mass accelerates slowly and deaccelerates slowly, which is why the body tend to move until another force (deacceleration) is affecting the body. The 150 ms time window was chosen based on the earlier studies which noted that noncontact ACL injuries are expected to occur between 0 and 61 milliseconds after initial contact, when the moments are at their biggest, according to Bates et al. (2020) and at 47 to 98 milliseconds after initial contact according to Ueno et al. (2021). The time after 150 ms was not taken under consideration, as the main purpose of this study was to examine the acute response of the rotational moments in the knees when wearing ski boots during a simulated balance perturbation. With the acute response we were aiming to concentrate on the possible injury time window.

9.3 Applications

The results can be applied to several different research aspects, equipment design and development, and training methods. First it has to be noted that additional research is needed on the effect of the ski boot on knee alignment, position and moments affecting the knee, as the research area is still lacking information. It would be important to concentrate more, especially on the ski boot properties, as it clearly has an effect on the knee moments and position. For example, the stiffness and the angle of the boot cuff (anterior-posterior), cuff height, broader view on the canting mechanism, spoilers, liners, insoles, and outside soles, could be inspected. It would be also important to dig even deeper into the effects of the ski boot on rotational moments, as according to Bürkner et al. (2008) further biomechanical studies examining the power transmission from ski boots to the lower leg, especially the rotational loads, would be needed. In addition, it would be important to test the effect of the ski boots in real conditions for example in outside in subzero temperatures (when the ski boot is stiffer), during skiing and real balance perturbation events (not only simulated events).

When designing and developing new ski boots the safety aspects and the possible mechanisms of the ski boot that could affect extra loading to the knee should be taken more into account. When selling and buying ski boots, it would be important to make sure to choose the right ski boot for the skier's level and to take into account the skiers anthropometrics. Especially important this would be for the beginners and the recreational skiers, as they often have more difficulties choosing the right ski boots for themselves. In ski racing the aggressivity and the performance aspects are unfortunately often more important for the athletes than the safety aspects. Which makes it hard to suggest safer and because of that maybe slower or less aggressive ski boots or other equipment to the athletes.

Lastly, the results of this study could be applied to physical training or for example balance training. Modern (i.e., carving) techniques need a strong sense of lateral and forward-backward balance because of the big inward leaning body angles (Müller & Schwameder 2003; Raschner et al. 2001). The ski boots could be used in physical training as a variation to shoes or bare feet to get to train the balance and to generate new (postural) balance methods. This could also be used when getting used to for example new ski boots (e.g., in the beginning of the season) or new or different ski boot settings. However, it must be remembered that it is also important to conduct physical training without ski boots during the competition and off season to strengthen the ankle and the muscle of the lower leg as very stiff ski boots can also act as an external ankle support which mechanically restricts the ankle motion and immobilize some muscles such as the gastrocnemius (Hauser & Schaff 1987). The ski boots can also affect the postural control, making the postural control for example less active (Noé et al. 2020). As Mildner et al. (2010), summarized, in addition to general physical training, skiers should utilize both general and ski-specific balance and sensimotor training which could help injury prevention, especially knee injuries. That is why varied training and versatile methods should be generally used.

9.4 Conclusions

In this study the effect of the ski boot on knee rotation moments, knee adduction moments and knee flexion angles were studied with help of a simulated perturbation protocol executed on an instrumented treadmill. The results indicate that the ski boots have an effect on the knee rotation moments, knee adduction moments and knee flexion angles on some level according to this and earlies studies. However, against the hypothesis, the ski boot did not significantly increase the knee rotational moments or knee adduction moments during balance perturbations. The results can be applied to several different research aspects, equipment design and development, and training methods. However, it must be noted that additional research is needed on the effect of the ski boot on knee alignment, position and moments affecting the knee, as the research area is still lacking information.

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