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Effect of ski boot settings on tibio-femoral abduction and rotation during standing and simulated skiing

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Abstract

Ski boots are designed to transfer high forces from the skier to the ski. For this purpose they are made of stiff materials and constrain the leg of the skier to an unnatural position. To overcome the problem of unnatural knee posture, the ski boots can be adjusted in the frontal plane as well as in the horizontal plane by the canting mechanism and the "v-position", respectively. Canting enables lateral and medial orientation of the shaft with respect to the base of the boot. The "v-position" is a pronounced outward rotation of the boot's base with respect to the ski's long axis. The purpose of this study is to investigate the effect of different foot rotations and ski boot canting settings on knee kinematics during standing and simulated skiing. Knee kinematics was measured by means of motion analysis and with the help of skin-mounted markers on 20 subjects.

The ski boots in their standard settings significantly constrained the skier to an unnatural valgus position. Ski boot base rotation had a significant effect on internal external knee rotation, whereas canting had an effect on varus–valgus angles during standing. However, for the simulated skiing position no effects were observed. The study suggests that the constraints of the ski boots result in a clinically relevant valgus misalignment. Canting settings reduced the misalignment but only by about 10%. Increased ski boot canting settings would therefore be desirable. Knee kinematics showed that rotational misalignment could not be linked to any significant increase in injury risk.

Keywords: Knee; Rotation; Varus and valgus; Ski boot; Canting

1. Introduction

Ski boots are made of stiff materials to transfer high forces from the skier to the ski (Maxwell and Hull, 1989). The drawbacks of stiff ski boots are that they constrain the skier's leg to an unnatural position, e.g. a skier with natural varus leg alignment is forced to a valgus movement in order to preserve parallelism of the ski to the ground (Corazza and Cobelli, 2005). Possible consequences of knee varus or valgus misalignment might be overuse injuries (Sharma et al., 2001, Teichtahl et al., 2006). Tibia-femoral rotation also alters the tibio-femoral articular cartilage contact points. This might change contact stress distributions in the cartilage and predispose the joint to degenerative changes (Li et al., 2006, Andriacchi et al., 2006). These long-term overuse effects of skiing in an unnatural position are difficult to assess, but deviations from normal posture are commonly taken as a risk factor for overuse injuries (Issa and Sharma, 2006). In addition to the risk of long-term overuse injuries, the risk of acute ACL ligament ruptures might be increased through knee misalignment. In dynamic landing movements, it has been shown that neutral limb alignment compared to varus or valgus reduces the possibility of ACL rupture through a valgus or varus opening mechanism (Chaudhari and Andriacci, 2006).

A less severe but very common knee injury is the patellofemoral pain syndrome (PFPS). Muscular imbalance of the lower extremity is one of the major contributing factors (Thomee et al., 1999). It might be speculated that knee misalignment, caused by the ski boot, places extra pressure on the muscles around the knee and possibly exaggerates muscle imbalances and patella grinding.

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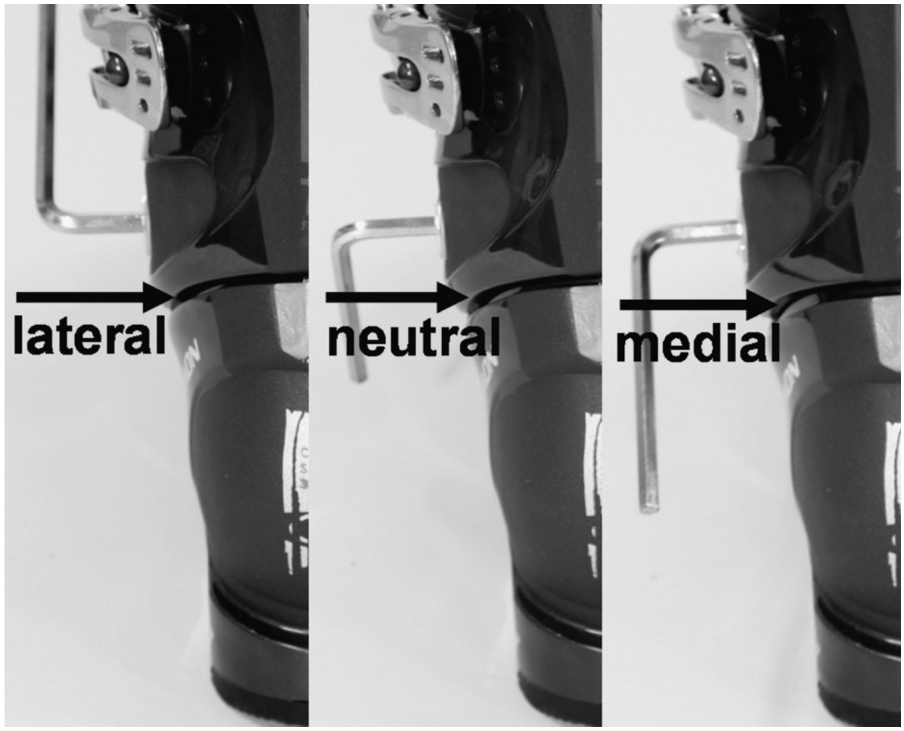

Fig. 1. Canting setting of the shaft with respect to the base of the ski boot is carried out continuously with an Allen key, from neutral to maximally medial and maximally lateral.

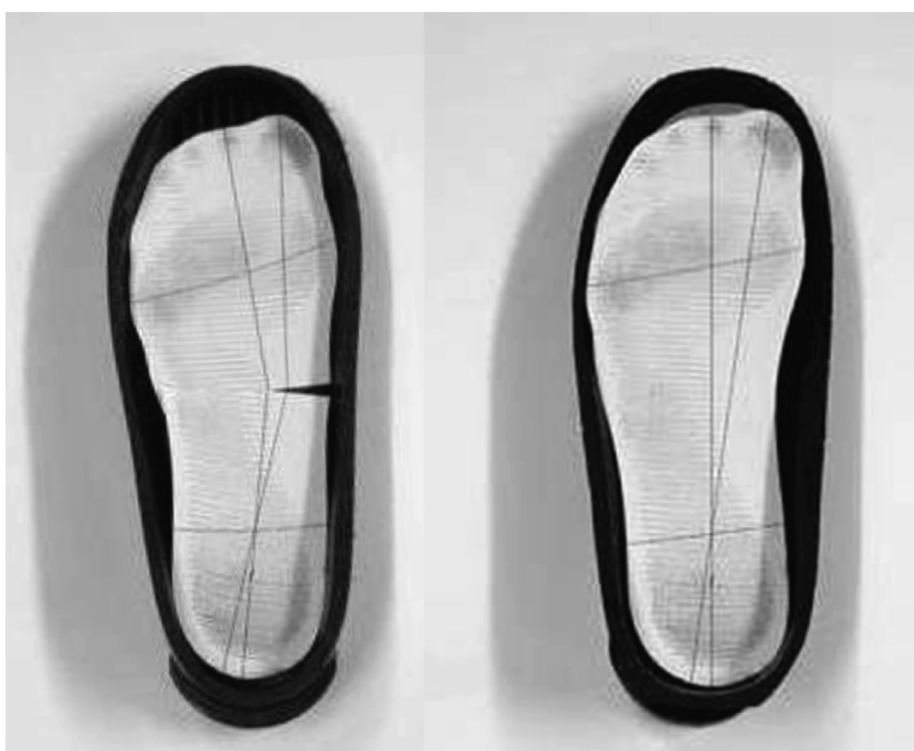

Fig. 2. Ski boot base rotation is realized by pivoting the sole around the midpoint about 9° as shown on the left side.

One solution to overcome the problem of unnatural knee posture is the canting mechanism offered by the majority of ski boot manufacturers. Canting enables lateral and medial tilting of the shaft with respect to the base of the boot (Fig. 1). Canting is supposed to adjust to individual varus or valgus posture. Another possibility to adjust the ski boot in the frontal plane was suggested by Corazza and Cobelli (2005). They designed a system that allows rotating

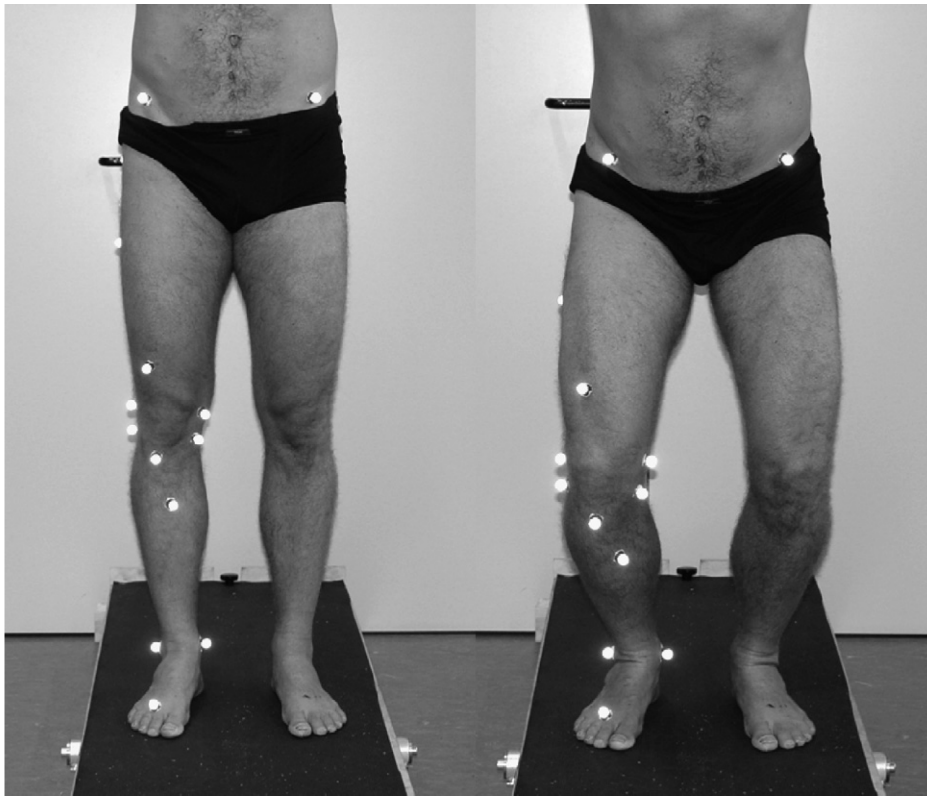

Fig. 3. Reference standing position left used to set up the joint coordinate systems. The right picture shows the squatting movement used to determine individual knee rotations at different knee extensions without ski boot. The palpated marker set on specific landmarks of the body enables us to calculate knee joint coordinate systems according to Grood and Suntay (1983).

the sole of the boot about the anterior posterior axis relative to the shell and cuff. This system is integrated into the sole and is locked into the desired position before skiing. The main drawback of this system is the large amount of local deformation that affects the stiffness of the overall system.

As previously mentioned, tibio-femoral malrotation is another important risk factor. A pronounced outward rotation of the base of the boot with respect to the ski direction would correspond more to the natural outward rotation of the foot (Schwarz et al., 1974). This so-called ''v-position'' with different pivoting points at the heel or at the mid-foot (Fig. 2) is enjoying increasing popularity among ski manufacturers.

During the turn, edging the ski into the snow causes external rotation of the tibia with respect to the femur of up to 5° and a valgus angle of 12° from neutral, measured by Yoneyama et al. (2000) and Greenwald et al. (1997), respectively. It is speculated that ski boot canting and base rotation reduces the observed valgization and internal rotation, respectively. To our knowledge, no investigations exist on the effect of ski boot canting setting or base rotation on knee kinematics; therefore the following two hypotheses were assessed in this study:

1. The ski boot in its standard setting (neutral canting and no base rotation) causes a significant statistical misalignment in the knee angles—both varus–valgus (VV) and internal–external rotation (IRER)—compared to the natural barefoot situation.
2. Canting and boot rotation have a significant statistical effect on knee VV and IRER angles, respectively.

The hypotheses were tested for both standing and simulated skiing situations.

2. Methodology

2.1. Experimental setup

Twenty subjects (15 m, 29 ± 6 years, 77 ± 9 kg, 175 ± 6 cm) participated in the study. Prior to participation all subjects were informed about the nature of the experiment and signed an informed consent. The subjects were all physically active and asymptomatic with no history of lower limb-, spinal- or neurological injury. The VV angles (measured via Q-angles) of the subjects during standing were in the range of values reported for normal subjects (Livingston and Mandigo, 1999).

First, the subjects had to perform eight knee flexion–extension (FE) cycles to define the individual VV and IRER angles without the ski boot intervention (Fig. 3). Thereafter, the subjects put on skis and ski boots and performed firstly an upright standing position (Fig. 4)—this occurs frequently during resting periods or lining up for the ski lift—and then a skiing position (Fig. 5) as it occurs during a turn. Both postures were carried out on a compensator (Figs. 4 and 5) to standardize the center of mass for each subject. The compensator joint was slightly damped to facilitate balancing. The ski boots were firmly tightened and the ski bindings were adjusted according to ISO 11088 (2006). In the standing position, the subjects were asked to take a comfortable position with the

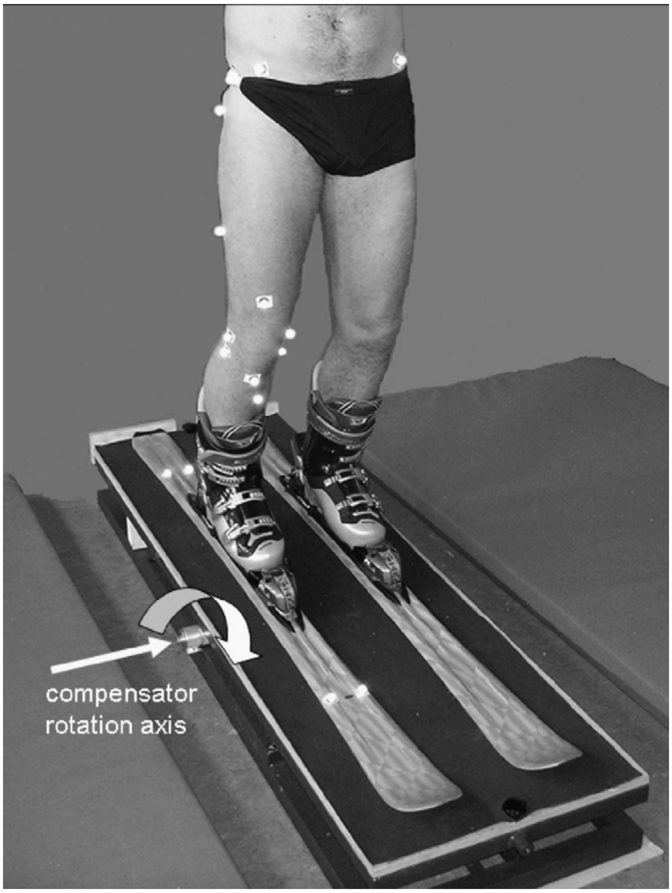

Fig. 4. The standing position on the dampened compensator responsible for the standardized center of mass movement of the subject. Unwanted ski movements were controlled by the markers attached to the ski.

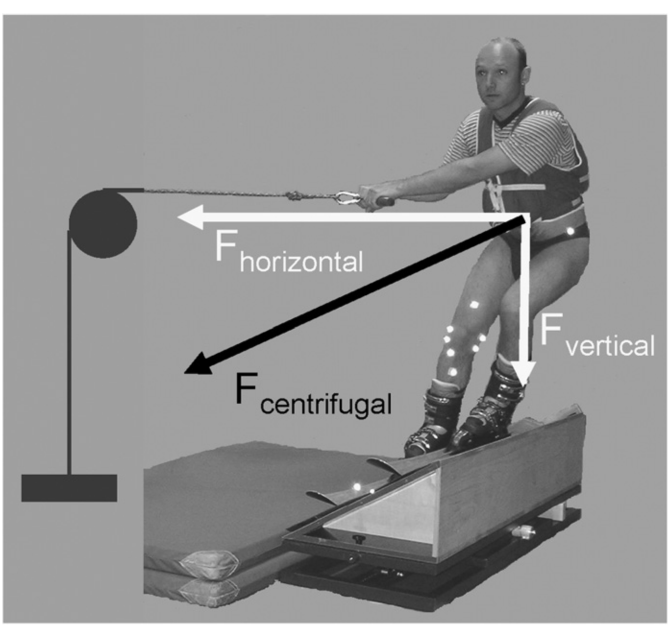

Fig. 5. Setup for simulated skiing. The centrifugal force is acting perpendicular to the angular velocity vector and is therefore parallel to the slope whose incline is 30°. The skis are in parallel position with the left ski about 1 ft in front of the right ski. The surface is covered with a rubber material providing enough friction to enable edging of the ski.

skis aligned parallel. Their position was then marked so that the same ski position would be maintained over all ski boot interventions. The subjects had to flex their knees, keeping their upper body upright, until the compensator was tilting forward. The subjects then had to balance eight times back and forth around this position by slightly flexing and extending their knees.

To simulate the skiing position on the slope, the horizontal plane of the compensator was tilted at 30°. The centrifugal force acting on the skier during the turn was perpendicular to the rotational velocity vector and therefore parallel to the slope (Fig. 5). The centrifugal force representing a speed of 30 km/h at a curve radius of 18 m was applied by two weights, one in a horizontal and one in a vertical direction, as shown in Fig. 5. For a subject with a bodyweight of 70 kg, the centripetal force was 270 N, so that the additional vertical and horizontal mass was set to 14 and 23 kg, respectively. The subjects were asked to stand with skis aligned parallel and the upper ski in front so that the hip was able to rotate to the right. The knees were flexed until the compensator started bending forward and in this position the subjects had to balance by slightly increasing and decreasing their knee flexion angle.

2.2. Materials

To vary the rotation of the foot in the shoe, a commercially available 9° (sb9, Fischer MX9) rotated shoe was used. A conventional shoe counterpart with a foot alignment of 0° (sb0, Salomon XWAVE) was chosen based on the same shaft stiffness measured according to IAS guidelines (IAS, 1980). The profiles of the two different ski boot bases are shown in Fig. 2.

The canting was set to maximal medial neutral and maximal lateral. Canting range is denoted by the manufacturers as $\pm 1°$ for medial and lateral adjustment from the neutral position (Fig. 1) for both the sb0 and the sb9 boot.

2.3. Determination of knee kinematics

The subjects knee kinematics was measured using skin-mounted markers, recorded with six cameras (Vicon MX-460, Oxford, UK) operating at 250 Hz. The focal volume of the cameras was limited to $2\,m^3$ to obtain optimal resolution of the 9 mm diameter reflecting markers. Markers were placed on anatomical landmarks shown in Figs. 3 and 4. Knee motion was expressed using Grood and Suntay's conventions (1983) (GSC) and employing Soederkvist and Wedin's (1993) transformation matrices.

To estimate the effect of kinematic crosstalk (Piazza and Cavanagh, 2000) on the knee VV and IRER angles, a sensitivity analysis of the orientation of the knee FE axis (aligned along the femoral condyles) was performed. This was done by rotating the knee FE axis $\pm 3°$ about the proximal GSC joint coordinate system X- and Y-axes, being perpendicular to the FE (Z) axis. Consequently, four different deviations of the standard femur (GSC) axis in different directions were used to show the effect on the VV and IRER angles calculated.

2.4. Data processing and statistical analysis

For each ski boot intervention, the subjects balanced eight times around their adopted position by slightly flexing and extending their knees. The IRER and VV angles occurring during these eight knee FE cycles were averaged using a linear fit over the varying FE angles. Based on this linear relation, IRER and VV angles were calculated at the average FE angle of all subjects during standing and simulated skiing. All IRER and VV angles during standing and simulated skiing were then calculated by subtracting the IRER and VV angles of the individual barefoot squatting position at the respective FE angle.

To evaluate the statistical significance of the ski boot intervention, a two-way repeated measures ANOVA (Keppel and Wickens, 2004) was used for the two factors, canting (medial neutral and lateral) and ski boot

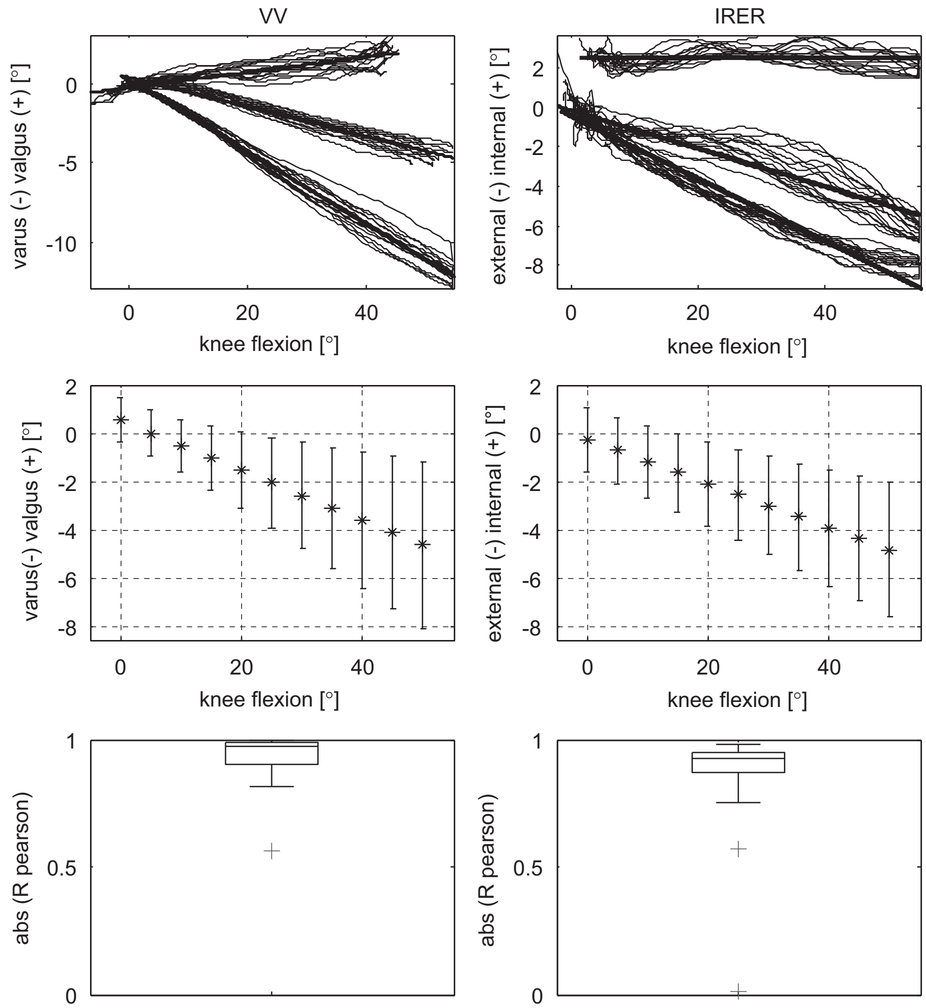

Fig. 6. Knee VV and IRER angles during barefoot squatting. The two upper graphs show the VV and IRER angles over eight knee flexion cycles. Displayed are the data of three subjects with the minimum, the maximum, and the average slope of the linear fit of the data. The box plot at the bottom shows the linear correlation coefficient calculated from the data in the upper graph on all 20 subjects tested. The middle graph displays average VV and IRER angles.

base rotation (sb0 and sb9). The significance level was set to 5%. Linear correlations between IRER, VV, and FE were determined using Pearson's method (Howitt and Cramer, 2004).

3. Results

3.1. Barefoot knee kinematics during squatting

Regarding the VV and IRER angles at the respective knee flexion angle during the eight FE cycles measured (Fig. 6), the graphs suggested a linear relationship between these parameters. The linear relationship was confirmed with the median of the absolute correlation coefficient, which was greater than 0.9 for VV and IRER (Fig. 6). For the VV angles, the majority of the subjects showed a negative correlation coefficient—this means an increased varus with increasing knee flexion. Only two subjects showed a positive correlation coefficient. For the IRER angles, all subjects showed a negative correlation coefficient—the so-called "screw home" motion: the tibia rotates internally to the femur with the knee extending to its neutral upright position. The size of the screw home motion from 50° flexion to full extension was $5.2 \pm 2.4°$. For VV, there was a similar observation: flexing the knee about 50° from full extension, the knee achieved a varus angle of $4.9 \pm 2.8°$. All mean values among the subjects and parameters tested showed a standard deviation that increased by about 100% from full extension to 50° knee flexion (Fig. 6). The sensitivity analysis of the femur axis direction revealed angular differences with respect to the original axis of $-0.7°$ to $2.0°$ and $-1.6°$ to $1.9°$ for VV and IRER angles, respectively, at knee flexions of 50°. The linear correlations between FE and IRER and between FE and VV remained unchanged.

3.2. Ski boot effects during standing

The mean FE angle of all subjects and all interventions during standing was $30.1 \pm 7.3°$. Compared to the corresponding individual barefoot position, the ski boots in

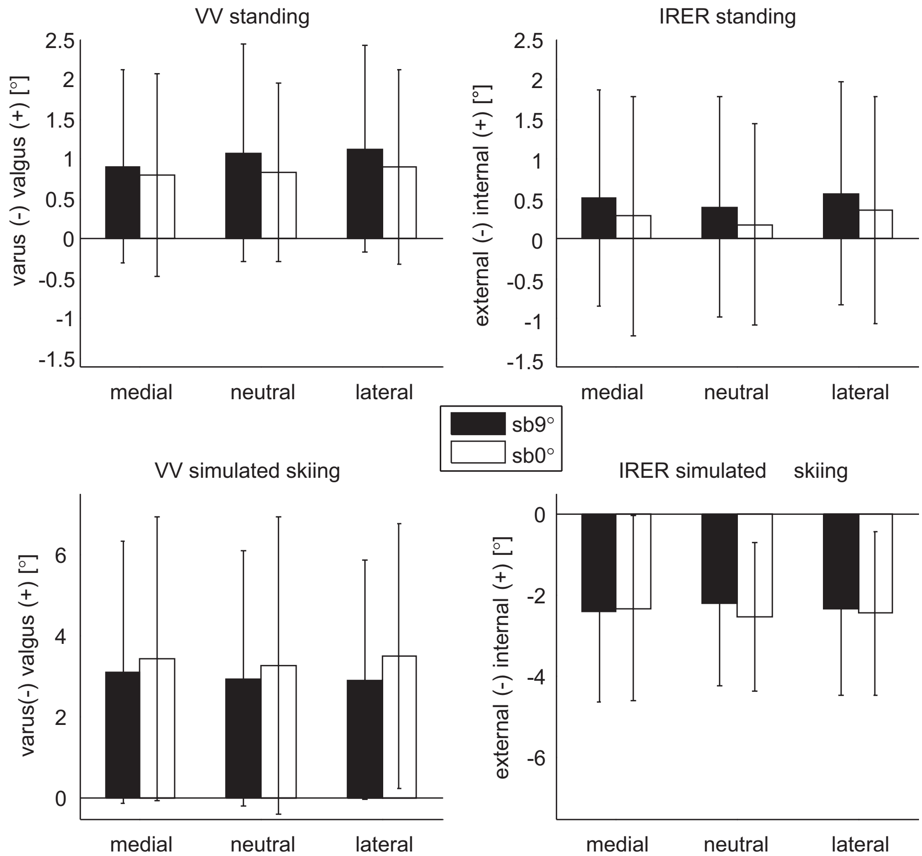

Fig. 7. Effect of ski boot interventions (canting and rotation) on VV and IRER angles during standing and simulated skiing. Displayed are the deviations from the neutral position (0°) without ski boot in the same knee flexion angle.

their default settings constrained the leg of the skier significantly ($p = 0.004$) to an unnatural valgus position of $0.8 \pm 1.1°$. The difference of $0.2 \pm 1.3°$ in IRER was not significant ($p = 0.053$).

In all interventions, ski boot rotation (sb9) showed about 0.2° higher mean values for IRER angles (Fig. 7). This was confirmed statistically: ski boot rotation had a significant effect on IRER ($p = 0.005$). The canting factor significantly affected VV ($p = 0.032$). The interaction between canting and rotation was in all cases not significant; therefore there was no evidence of a synergistic (interaction) effect between the two factors. The sensitivity analysis showed $-0.032°$ to $0.071°$ and 0.003–0.074° changes for VV and IRER angles, respectively.

3.3. Ski boot effects during simulated skiing

The mean FE angle of all subjects and all interventions during simulated skiing was $45.8 \pm 8.9°$. Compared to the corresponding individual barefoot position, the ski boots in their default settings constrained the leg of the skier significantly ($p < 0.001$) to an unnatural valgus position of $3.3 \pm 3.7°$. The shank was significantly ($p < 0.001$) externally rotated $-2.5 \pm 1.8°$ with respect to the thigh and the individual neutral position. The statistical analysis did not show any significant effect of rotation or canting on VV and IRER angles. The sensitivity analysis demonstrated angular differences from $-0.06°$ to $0.01°$ and $0.02°$ to $0.07°$ for VV and IRER angles, respectively.

4. Discussion

Comparing knee kinematics of the simulated skiing positions to those measured during outdoor conditions; mean knee flexion angles of $45.8 \pm 8.9°$ were close to the average knee angles of 50°, measured by Yoneyama et al. (2000) at the outside leg during a left turn. In this study, external rotation of the shank with respect to the thigh was $2.5 \pm 1.8°$ relative to the situation without ski boots. The absolute values relative to upright standing were $7.0 \pm 3.4°$, which is within the range of rotation measured during outdoor skiing, i.e. 5° (Yoneyama et al., 2000). The knee angles measured are comparable to those measured by other authors; therefore we are confident in testing the two hypotheses on the effects of ski boots on knee kinematics as formulated in Section 1.

The first hypothesis, i.e. the ski boot in its standard setting causes a significant knee misalignment during standing and simulated skiing, was true for VV angles in both situations. For IRER, it was significant only during skiing. The average VV misalignment caused by the ski boot was $0.8 \pm 1.1°$ and $3.3 \pm 3.7°$ valgus for the standing and skiing situation, respectively. None of both situations caused a valgus misalignment of more than 5° which significantly increases the risk of osteoarthritis progression (Sharma et al., 2001). The time spent on recreational skiing is minimal compared to that spent on daily life activities; therefore overuse is not the primary concern. The most important effect might be the increased risk of non-contact ACL injuries caused by valgus misalignment. It has been shown that shifting the valgus alignment by 2° dropped the injury threshold by one bodyweight (Chaudhari and Andriacci, 2006). Furthermore, valgus misalignment places the tibial tuberosity more laterally, causing lateral tracking of the patella which might be associated with PFPS, particularly in combination with increased physical activity as it occurs during skiing (Thomee et al., 1999).

While the observed valgus angles can lead to an increased risk of ACL injuries and PFPS, the risk of ACL injuries due to rotational offset was investigated in the literature to a lesser extent. Passive rotation limits for the knee joint are 25° and 40° for internal and external rotation, respectively (Zarins et al., 1983). Patellofemoral joint pressure in excess of 20° rotation is a potential predisposing factor of PFPS (Cheung et al., 2006). Since rotational offsets in this study were a lot smaller ($2.5 \pm 1.8°$), the risk regarding IRER misalignment is not considered to be relevant.

The second hypothesis, i.e. the ski boot interventions have an effect on knee kinematics, was significant during standing and not significant during simulated skiing. In the standing situation, canting had an effect on VV whereas boot rotation had an effect on IRER. As mentioned above, the IRER misalignment is not considered to be clinically relevant. Therefore, only the effect of the canting setting on VV needs further attention. The effect of the canting setting on VV angles is maximally 10% of the misalignment (Fig. 7) and therefore not clinically relevant to reduce the valgus misalignment caused by the ski boot.

As is the case with all assessments of in vivo joint motion, the accuracy of the results is limited by the use of skin markers. Marker movement relative to the bone is not of particular concern for the slow and low impact movements in this study; it occurs predominantly during high dynamic activity (Ramsey and Wretenberg, 1999). Another known problem in knee joint kinematics is the fact that VV and IRER angles are small relative to the FE motion, and therefore they are easily influenced by minor variations in the definition of the knee flexion axis (Piazza and Cavanagh, 2000). The effect of this ‘‘kinematics crosstalk’’ problem was quantified by a sensitivity analysis at varying FE axis directions. The sensitivity analysis showed changes of maximally 2° in the calculated VV and IRER angles during barefoot knee flexion. In the ski boot intervention, the average IRER and VV angles did not differ noticeably (maximally 0.07°) when the corresponding individual knee angles during barefoot squatting were subtracted. Normalization on barefoot flexion reduced the error considerably so that the small interventions to the ski boot could be observed during standing, but not in simulated skiing. One reason might be that with increasing knee flexion the standard deviation of the subject's mean values becomes higher (Fig. 6). This might be a result of increased marker movement caused by the skin, or of neuromuscular differences between the subjects (this has more effect when the knee is in a flexed position). In the position close to full extension, rotation of the knee is almost completely restricted by the interlocking of the femoral and tibial condyles (Nordin and Frankel, 1989). Consequently, the ski boot intervention in the constrained standing position, with an average knee flexion of 30°, demonstrates a clear effect on VV and IRER angles. In the skiing situation with a larger knee flexion of 46° as well as unrestricted ski canting angles of $24.1 \pm 2.6°$, these effects could not be resolved. This is in accordance with observations in running: even when skin artifacts are reduced by using bone pins (Stacoff et al., 2000), the shoe interventions produce substantially different results for different subjects so that no effects can be observed. One reason for this observation was suggested by Nigg et al. (2003) that humans act differently on the interventions in the shoes. Unrestricted free running as well as simulated skiing allows for enough freedom to perform different movements; therefore intervention effects on knee kinematics are extremely difficult to assess in both cases.

In this study, it was shown that ski boots caused a significant valgus and external rotation misalignment of the knee. There is strong evidence in the literature to suggest that the valgus misalignment may increase the risk of injury. The canting and rotation ski boot settings were shown to have an effect on the VV and IRER, respectively, during standing. However, in their present range, rotation and canting setting were not sufficient to eliminate the misalignment measured. For the canting setting, in particular, a bigger range would be recommended, considering the great risk of valgus misalignment.

Conflict of interest statement

Both authors do not have any financial and personal relationships with other people or organizations that inappropriately influence the work performed.

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