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Research article

Multi-Axis Prosthetic Knee Resembles Alpine Skiing Movements of an Intact Leg

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Abstract
The purpose of the study was to analyse the flexion angles of the ski boot, ankle and knee joints of an above-knee prosthesis and to compare them with an intact leg and a control group of skiers. One subject with an above-knee amputation of the right leg and eight healthy subjects simulated the movement of a skiing turn by performing two-leg squats in laboratory conditions. By adding additional loads in proportion to body weight (BW; +1/3 BW, +2/3 BW, +3/3 BW), various skiing regimes were simulated. Change of Flexion Angle (CoFA) and Range of Motion (RoM) in the ski boot, ankle and knee joints were calculated and compared. An average RoM in the skiing boot on the side of prosthesis (4.4 ± 1.1°) was significantly lower compared to an intact leg (5.9 ± 1.8°) and the control group (6.5 ± 2.3°). In the ankle joint, the average RoM was determined to be 13.2±2.9° in the prosthesis, 12.7 ± 2.8° in an intact leg and 14.8±3.6 in the control group. However, the RoM of the knee joint in the prosthesis (42.2 ± 4.2°) was significantly larger than that of the intact leg (34.7 ± 4.4°). The average RoM of the knee joint in the control group was 47.8 ± 5.4°. The influences of additional loads on the kinematics of the lower extremities were different on the side of the prosthesis and on the intact leg. In contrast, additional loads did not produce any significant differences in the control group. Although different CoFAs in the ski boot, ankle and knee joints were used, an above-knee prosthesis with a built-in multi-axis prosthetic knee enables comparable leg kinematics in simulated alpine skiing.

Key words: Above-knee amputation, Alpine skiing, impairment, kinematics, prosthesis.

Introduction

Alpine skiing is a popular winter sport. In addition to healthy skiers, a significant proportion of people with amputated legs also ski (O'Leary, 1994), and the associated types of skiing are categorized based on amputation severity. People with a below-knee amputation of one leg can ski with or without an artificial limb (i.e., a prosthesis) (Bowker et al., 1992). The majority of people with an above-knee amputation skiing on an intact leg use the so-called three-track skiing technique (Miller, 2002), which involves skiing on their intact leg only while using special poles (i.e., crutches) with skis fixed at their ends. With a below-knee amputation of both legs, skiers use the four-track technique, which uses two crutches in addition to two skis. People with an above-knee amputation of both legs can ski using short prostheses without a knee mechanism or use a sit-ski or mono-ski (Cavacece et al., 2005, Gegenwarth and Reinelt, 2010).

Regular skiing on both legs (intact legs and prosthetic) is rarely used by people with an above-knee amputation. The majority of artificial limbs are designed for walking purposes only. The kinematics and particularly dynamics of the legs while skiing are significantly different than those while walking. During walking, there is a small knee flexion in the stance phase and large in the swing phase (Segal et al., 2006), while during skiing, there is a large flexion in the knee joint through the entire turn (Kröll et al., 2010, Yoneyama et al., 2000). In addition, the loads of the legs during walking are overall significantly lower than while skiing. The additional loads which were the results of the movement of a skier during a turn, often reaches the values more than one body weight (BW) (Yoneyama et al., 2000).

According to previous studies, practical experience and preliminary testing, it can be assumed that prostheses made-for-walking are not suitable for regular two-track alpine skiing. In walking, dorsal flexion in the ankle joint is approximately 15°, and knee flexion is near 60° (Ounpuu, 1994, Segal et al., 2006). Measurements in alpine skiing have shown that dorsal flexion in the ankle joint is between 20° and 30° (Petrone et al., 2013), and knee flexion is between 60° in the outside leg and 90° in the inside leg (Kröll et al., 2010). A second discrepancy occurs during the transfer of load; the torques in the ankle and knee joints are much smaller during walking (Novacheck, 1998) compared to alpine skiing (Klous et al., 2012). Artificial limbs made for walking have a built-in passive prosthetic knee joint that can resist only limited torques in the ankle and knee joints during the flexion phase and minimum torques in the extension phase (Segal et al., 2006).

The ski boot has the important role of ensuring appropriate kinematics and dynamics of the lower extremities during alpine skiing. Their function is not only to protect the foot/ankle/tibia complex from environmental and mechanical loadings but also to ensure correct and efficient load transmission to the skis through the bindings while enabling the skier to assume the desired skiing posture during downhill, turning, jumping or stopping manoeuvres (Böhm and Senner, 2008; Petrone et al., 2013). Field measurements have shown that the maximum ski boot flexion ranges from 6.7° in a racing boot to 10.9° in a soft boot (Petrone et al., 2013).

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Sports activities, such as alpine skiing, require strength in *m. quadriceps femoris*, which requires special types of artificial limbs, particular knee joints which provide appropriate kinematics and dynamics. To the authors' knowledge, there are only two types of artificial knee joints available on the market that allow for regular two-track skiing; the oldest single-axis artificial knee joints (e.g., XT9 ESPK, Symbiotech, USA) and multi-axis prosthetic knee joints (e.g., ART-LEG Sport knee, Art-leg, Slovenia), which were developed more recently. The multi-axis knee prosthesis was developed to overcome anecdotal problems in balance when using a single axis prosthetic knee, where the skier is unable to push the prosthetic knee forward in a way that is similar what a healthy skier can do on a healthy leg. The virtual pivot point of the multi-axis knee moves forward and thereby provides virtual dorsal flexion in the ankle joint, while knee flexion occurs (Demšar et al., 2011).

The purpose of the study was to simulate skiing conditions in the laboratory and to analyse flexion in a ski boot, ankle and knee joints for a skier with a special above-knee prosthesis for alpine skiing. Further, the aim was to compare the results of prosthesis with the results of an intact leg and a control group of regular skiers. The hypothesis was that an above-knee artificial limb with a multi-axis prosthetic knee made for alpine skiing permits similar kinematics to an intact leg. In addition, we analysed the effect of additional loads on the flexion in the ski boot, ankle and knee joints.

Methods

Participants

This study examined one subject with an above-knee amputation of the right leg (the amputee) and eight healthy professional skiing instructors, who are members of the Demo Team Slovenia (the control group). Amputee used to be an active skier and a skiing instructor prior to an accident in 2008, when his right leg was amputated. Currently, to ski, he uses a special prosthesis with a multiple-axes prosthetic knee joint and a rigid ankle connection (i.e., locked ankle joint). All subjects have participated in this study voluntarily and have given written informed consent. The study has been performed according to the Helsinki Declaration and was also approved by the local ethics commission at the Faculty of Sport, University of Ljubljana, Slovenia.

Experimental setup and data collection

Measurements of the kinematics of the lower extremities during two-leg squats, which were used to simulate leg kinematics during skiing turns, were performed in a purpose-built test device that allowed changes in vertical loading (Demšar et al., 2011). Additional loads up to one body weight, were simulated using extra weights, which were fixed with a special leather belt at waist height using special low friction rope-pulley systems. Measurements included one set of measurements without and three sets with +1/3, +2/3 and +3/3 BW of additional load. In order to avoid the fatigue, which might affect on the implementation of measurements, the largest load represented less than half of 1 repetition maximum.

Next to different loads, also different cycle times were tested. Cycle times (e.g., 0.85 and 1.25 s) were selected according to previous studies of gate-to-gate times during a slalom turn (Supej and Holmberg, 2011). Cycle times were dictated by an electronic metronome. Subjects warmed up before measurements while also performing short measurement tests with different loads. Subjects executed at least twenty repetitions at lower and twenty at higher frequencies of movement for each measurement. To reduce the possibility of fatigue, the order of the four measurements with different loads were selected randomly. Each measurement was followed by an eight-minute rest period, and a 20-minute break was applied between the two series.

For the amputee, kinematic measurements were performed on both legs: the right leg had the prosthesis, and the left was intact. In the control group, measurements involved only the subjects' right legs. From the entire sample of repetitions/cycles at each frequency and at each load, a uniform random function was used to select 10 repetitions/cycles for analysis. Measurements were performed in an air-conditioned laboratory at 18°C.

Instruments

Motion capture with retro-reflective markers was used to record the movement of the subjects' lower extremities. The locations of the reflective markers were selected to allow monitoring of each individual extremity segment (prosthesis and intact leg) with three degrees of freedom. Markers A, B and C were placed on the ski boot. On the prosthetic leg, marker D was placed on the lower axis and marker E on the upper axis of the artificial knee joint; and marker F was placed on the top of the socket. On the intact legs, marker D was placed on the calf just above the ski boot, marker E was placed on the knee joint and marker F was placed on the hip joint (Figure 1).

Images of the locations of reflective markers in the sagittal plane were captured using two high speed cameras Casio Exilim EX-F1 (Casio Computer Co., LTD, Tokyo, Japan). Frame captures were recorded at 60 frames per second in Full High Definition resolution (1920 x 1080 pixels). Cameras were placed laterally on the right and left side of the measured subjects to capture the view of the sagittal plane. Depth measurement error was minimised by decreasing the viewing angle, and an ample zoom was used to achieve a pixel size of less than 1 mm. Digitisation of the reflective markers was performed with the Ariel Performance Analysis System (APAS; Ariel Dynamics Inc., San Diego, CA).

Calculations

Angles between the individual segments were calculated from the marker positions (Figure 2). The ski boot angle (φ_{SB}) is represented by the angle between the bottom (markers A, B) and top (markers B, C) part of the ski boot:

$$\cos \varphi_{SB} = \frac{|\overline{BC}|^2 + |\overline{BA}|^2 - |\overline{CA}|^2}{2\,|\overline{BC}|\,|\overline{BA}|} \quad [1]$$

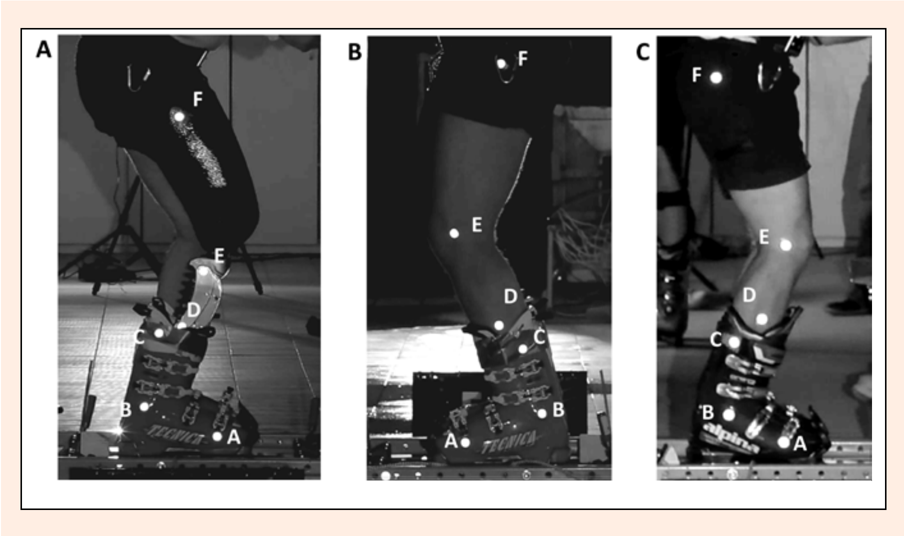

Figure 1. **Location of reflective markers: (A) amputee – prosthetic (right) leg, (B) amputee – intact (left) leg, (C) control group – right leg.**

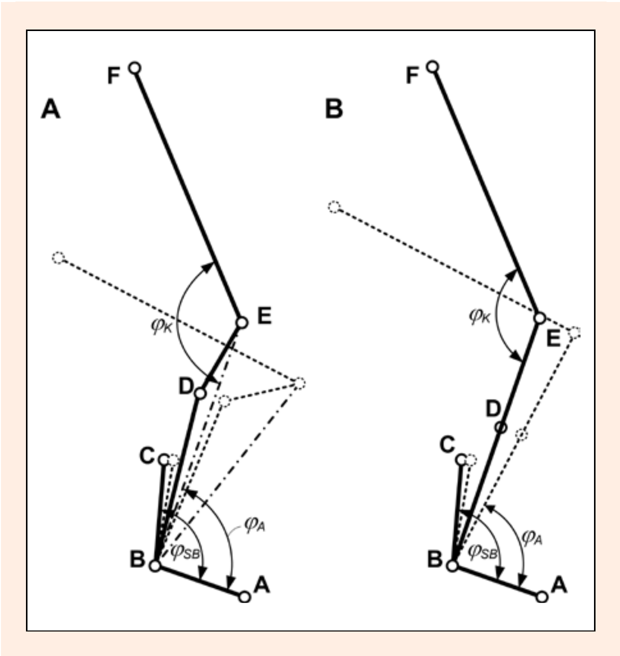

Figure 2. **Kinematic model of the leg in skiing; (A) prosthetic leg, (B) intact leg. φ_{SB} – ski boot angle, φ_A – ankle joint angle, φ_K – knee joint angle.**

The ankle joint angle (φ_A) is represented by the angle of the bottom part of a ski boot (markers A, B) and the lower leg (markers B, E):

$$\cos \varphi_A = \frac{|\overline{BE}|^2 + |\overline{BA}|^2 - |\overline{EA}|^2}{2\,|\overline{BE}|\,|\overline{BA}|} \qquad [2]$$

The knee joint angle (φ_K) is represented by the angle between the lower (markers B, E) and upper leg (markers E, F):

$$\cos \varphi_K = \frac{|\overline{EB}|^2 + |\overline{EF}|^2 - |\overline{BF}|^2}{2\,|\overline{EB}|\,|\overline{EF}|} \qquad [3]$$

Because the angles in the ski boot, ankle and knee joints depend on the initial placement of the control points and must ensure that a comparison between an intact leg and the prosthetic leg would be valid. Changes of Flexion Angles (CoFAs) were used instead of the regular biomechanical angles. CoFAs in the ski boot, ankle and knee joints were calculated as the differences between the largest measured angle within one set of measurements, and a momentary angle. The peak CoFA was the largest CoFA, which was achieved within one set of measurements. The Range of Motion (RoM) was calculated as the difference between the maximum and minimum joint angle of each cycle.

An individual set of measurements for up-down movements were divided into individual cycles, simulating the movement of a skier during a turn. One cycle represents the movement from the highest position (i.e., the maximum angle in the knee joint, 0% of a cycle) to the lowest position (i.e., the minimum angle in the knee joint, 50% of a cycle) and back to highest position (i.e., 100% of a cycle).

Statistical analysis

Lilliefors and Shapiro-Wilk statistical tests were used to test the normality of the distribution of the cycle time and the RoM for each measured subject. Two-sample T-test (normally distributed samples) and Wilcoxon signed-rank test (not normally distributed samples) were used to test the effect of the cycle time on the leg kinematics during the up-down movement. The effect of additional load on the RoM of the ski boot, ankle and knee joints was tested with a one-way ANOVA and a multiple comparison test. A double-sample two-tailed T-test and Wilcoxon signed-rank test were also used to compare the RoM of the prosthetic (right) and intact (left) leg. Statistical tests were deemed significant at $\alpha = 0.05$. The results are presented as average values ± standard deviation. All calculations and statistical tests were performed using Matlab 2007a (Mathworks Inc., Natick, MA).

Results

Influence of frequency

The frequency of the up-down movements is shown to not have a significant influence on the RoM of the ski boot,

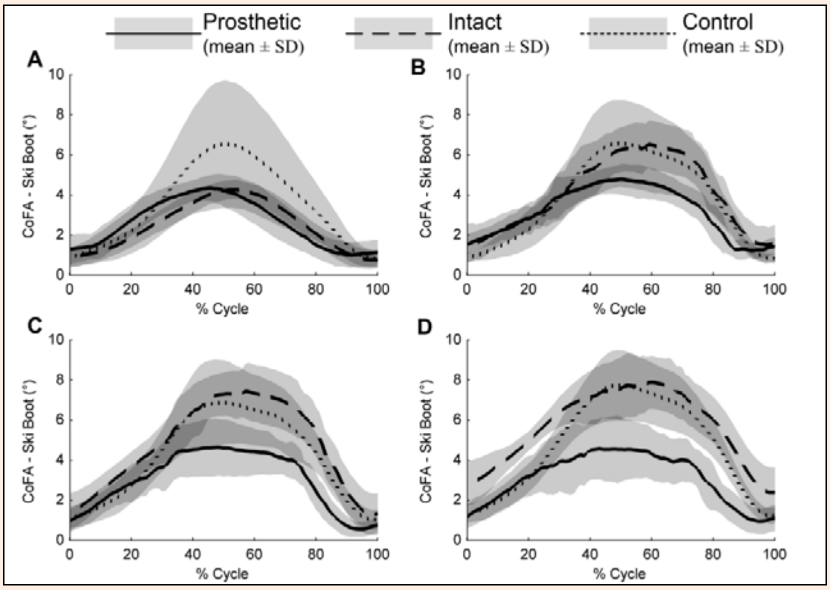

Figure 3. **Average interpolated CoFAs in the ski boot according to the cycle interval. (A) without additional load, (B) with 1/3 BW of additional load, (C) with 2/3 BW of additional load, (D) with 3/3 BW of additional load.**

ankle and knee joints in most cases. Therefore, in order to include various regimes of skiing, the measurement results of both frequencies of movement were combined. The average cycle times in Amputee vs Control were 1.0 ± 0.2 vs 1.0 ± 0.1 sec for + 0BW; 0.9 ± 0.2 vs 1.0 ± 0.1 sec for +1.3 BW; 0.9 ± 0.1 vs 1.1 ± 0.1 sec for +2/3 BW; 1.0 ± 0.2 vs 1.0 ± 0.1 sec for +3/3 BW.

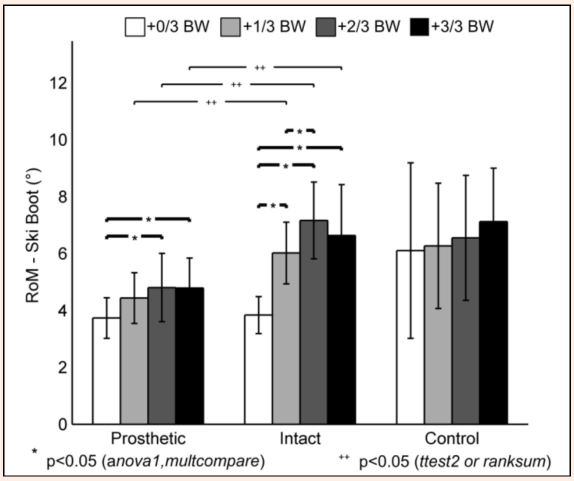

Figure 4. **RoM in the ski boot of the amputated skier (prosthetic and intact leg) and the control group.**

Ski boot

The average peak CoFAs in the ski boot were found to be 5.4 ± 1.1° (Prosthetic leg), 8.7 ± 1.2° (Intact leg) and 8.1±1.7° (Control group). Figure 3 presents the average interpolated CoFA in the ski boot throughout an entire cycle (i.e., a ski turn) with different additional loads.

The average RoM in the ski boot was measured to be from 3.7 ± 0.7° to 4.8 ± 1.2° (prosthetics leg), 3.8 ± 0.7° to 7.2 ± 1.3°(intact leg) and from 6.1 ± 3.2° to 7.1 ± 1.9° (control group).

On the prosthetic leg, the RoM in the ski boot without any additional load was found to be significantly lower compared to that with additional loads of +2/3W and 3/3BW. The RoM in the ski boot on the intact leg was significantly different in all cases instead of with additional loads of +2/3 and +3/3 BW. Measurements of the control group showed no effect from the additional loads on the RoM in the ski boot. Comparison between the prosthetic and intact leg revealed a significant difference in all cases except in the case without additional load (+0/3 BW) (Figure 4).

Ankle joint

The average peak CoFAs in the ankle joint were found to be 14.9 ± 3.0° (Prosthetic leg), 16.8 ± 1.0° (Intact leg) and 17.2 ± 2.3° (Control group). Figure 5 shows the average interpolated CoFAs in the ankle joint throughout an entire cycle. As shown, differences are present throughout the entire cycle in both the means and standard deviations with different additional loads.

The average RoMs in the ankle joint of all measurements were 13.2 ± 2.9° on the prosthetic leg, 12.7 ± 2.8° on the intact leg and 14.8 ± 3.6° in the control group. Depending on the additional load, the RoMs in the ankle joint measured from 12.1 ± 2.2° to 14.4 ± 3.1° (prosthetic leg), 9.6 ± 1.6° to 15.2 ± 2.1°(intact leg) and 13.7 ± 5.3° to 15.7 ± 2.4° (control group).

The RoM in the ankle joint on the prosthetic leg without additional load was significantly lower compared to that with an additional load of +2/3BW and significantly higher compared with the intact leg. On the intact leg, a significant difference between the RoM in ankle joint was found in all cases except between those cases with additional loads of +1/3 BW and +3/3BW. Measurements of the control group showed no effect of additional loads on the RoM in the ankle joint (Figure 6).

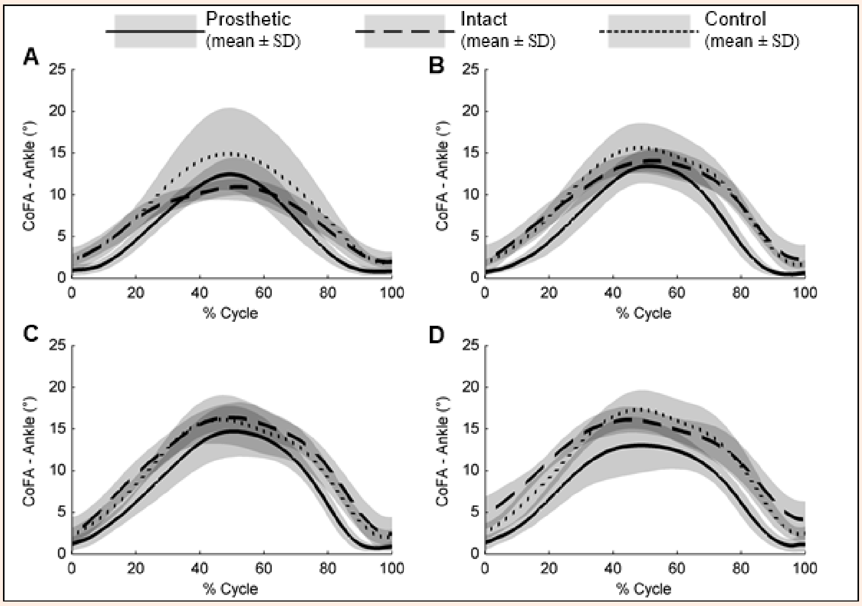

Figure 5. Average interpolated CoFAs in the ankle joint according to the cycle interval. (A) without additional load, (B) with 1/3 BW of additional load, (C) with 2/3 BW of additional load, (D) with 3/3 BW of additional load.

Knee joint

The average peak CoFAs in the knee joint were found to be 48.6 ± 3.7° (prosthetic leg), 40.0 ± 4.2° (intact leg) and 51.5 ± 4.6° (control group). Figure 7 shows the average interpolated CoFAs in the knee joint throughout an entire cycle. In the Amputee, the CoFAs of the prosthetic knee were larger than those in the intact knee; however, this difference decreased with increasing additional load.

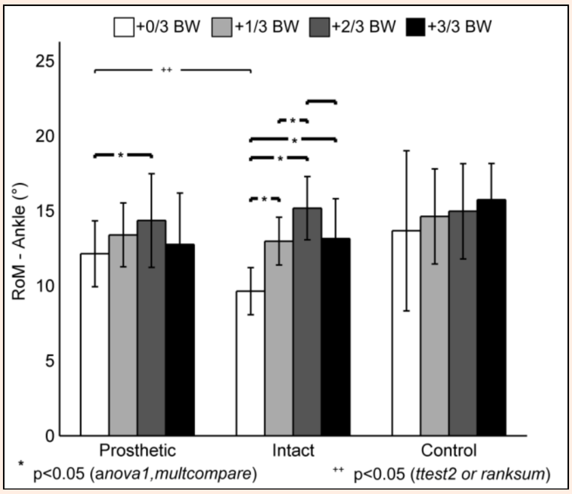

Figure 6. RoM in the ankle joint of the amputated skier (prosthetic and intact leg) and the control group.

The average RoMs in the knee joint of all measurements were 42.2 ± 4.2° on the prosthetic leg, 34.7 ± 4.4° on the intact leg and 47.8 ± 5.4° in the control group. Depending on the additional load, the lowest average RoMs in the knee joint were measured in the case of one additional load +3/3 BW: 37.8 ± 3.1° (prosthetics leg), 32.4 ± 2.7° (intact leg) and 46.7 ± 6.2° (control group). The highest measured RoMs were 45.1 ± 3.3 (+1/3 BW) (prosthetics leg), 36.6 ± 3.3° (+2/3 BW) (intact leg) and 48.6 ± 4.4° (+1/3 BW) (control group).

Additional load is shown to have a significant influence on the RoM of the prosthetic knee. At one body weight (+3/3 BW) of additional load, the RoM in the prosthetic knee is significantly lower than those in the other cases. For the intact leg, the RoM in the knee joint with +3/3 BW of additional load is also significantly below in case of +2/3 BW and +1/3 BW. Measurements of the control group showed no effect due to additional loads on the RoM in the knee joint. Between the prosthesis and the intact leg, there are significant differences in the RoMs in the knee joint in all cases (Figure 8).

Considering the initial flexion of the knee (40° in the prosthesis, 50.6 ± 5.9° in the intact leg and 35.4±6.5° in the control group) and the associated RoMs, it can be estimated that the total flexion in the knee was near 85° in all cases.

Discussion

This study presents the results of measurements of the flexion in ski boot, ankle and knee joints in simulations of different regimes of skiing with a special above-knee prosthesis with a multi-axis knee joint, which has been successfully used for actual skiing. The primary findings of the study were that: 1) the RoMs in the ski boot on the side with the prosthetic leg were smaller than the RoMs on the side of the intact leg and in the control group; 2) the RoMs in the ankle joint in the prosthesis were similar to those in the intact leg and the control group; 3) the RoMs in the prosthetic knee were greater than the RoMs in the knee joint of the intact leg and smaller than those in the control group; and 4) additional loads have a significant influence on the flexion in the ski boot, ankle and knee joints for both the Amputee's prosthetic and intact legs. In the control group, the influence of additional load

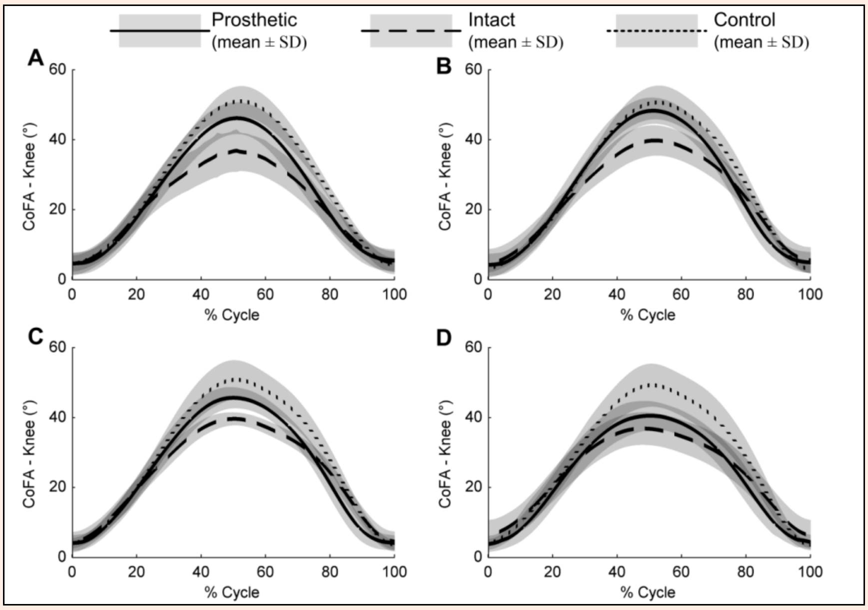

Figure 7. Average interpolated CoFAs in the knee joint according to the cycle interval. (A) without additional load, (B) with 1/3 BW of additional load, (C) with 2/3 BW of additional load, (D) with 3/3 BW of additional load.

could not be statistically confirmed.

Smaller flexion in the ski boot on the side of the prosthetic leg can be attributed to the construction of the bottom part of the artificial limb, which does not allow flexion between the lower leg and the prosthetic foot (Reichel et al., 2008). This can be partly mitigated with a deformation in the prosthetic foot and movement of the prosthesis within the ski boot (Demšar et al., 2011). Flexion of the ski boot in addition to the corresponding kinematics, in conjunction with the stiffness of the ski boot, also provides an appropriate moment, and thus, the load can be effectively transferred from the leg to the ski. In the case of the prosthesis with a rigid connection between the lower leg and the foot, most of this load is transferred through the feet directly to the underside of the ski boot. Greater flexion in the ski boot on the side of the prosthesis can be achieved by releasing the attachment between the lower part of the leg and the foot (i.e., ankle flexion). The problem in this case is that the Amputee has no control of that movement.

Despite the rigid connection between the lower part of the prosthesis and the prosthetic foot, virtual flexion in the ankle has been achieved. As mentioned earlier, a portion of that flexion is associated with the prosthesis moving within ski boot; a portion of this is a product of the structure of the knee joint, and combined with flexion, it provides forward movement of the knee with virtual dorsal flexion of the ankle. Sufficient dorsal flexion of the ankle is essential to maintain the balance during upward or downward movement, which is also implemented in the derivation of the ski turns. The measurements show that the CoFAs in the ankle joint are comparable between the prosthesis, the intact leg and the control group.

Total dorsal flexion of the ankle thus amounts to approx. 30 ° (flexion point approx. 15° + ROM approximately 15°), which is significantly more than when walking (Novacheck, 1998). Conversely, when skiing, there is no plantar flexion of the ankle, while during walking, it is approximately 10° in normal gait and less than 5 ° for walking with a prosthesis (Segal et al., 2006). This also confirms the assertion that prostheses for walking are not suitable for alpine skiing based on their kinematics.

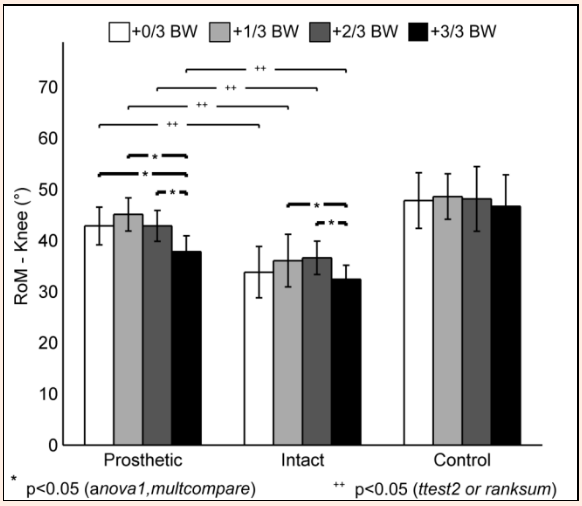

Figure 8. RoM in the knee joint of the amputee (prosthetic and intact leg) and the control group.

Although the measured RoMs in the prosthetic knee were significantly higher than those of the intact leg, while, at the same time, somewhat smaller than those in the control group, the total flexion was similar in all cases. This can be associated with an initial flexion in the knee joints. In the case of the subject with an above knee amputation, the initial position was specified from the construction of the prosthesis and was always the same. Due to the specific form of the prosthesis and the prosthetic knee joint, the initial flexion in the prosthesis was smaller than in the intact leg and much higher than in the control group, where the initial position was defined by the basic skiing posture.

For the amputee, it has been shown that by increasing the additional load (+1/3 BW in the prosthesis, +2/3BW in the intact leg), flexion in the knee decreases. This can probably be explained by the fact that increased additional vertical load causes increased torque in the knee joint. The torque in the knee joint also increases with knee flexion. We assume, there is an upper limitation to the torque in knee joint that causes additional vertical loads to create smaller flexion in the knee joint. This upper limitation of the torque in the prosthesis depends on the dynamic characteristics of the prosthetic knee, which provides a specific torque at a certain flexion. Probably, increasing the torque over the above mentioned limit was first compensated with the increased torque in the healthy leg and then by reducing the knee flexion. However, to confirm this assumption, the future plan is to perform dynamic measurements and analysis.

The total knee flexions measured in the alpine skiing simulations are significantly larger than the flexion measured during walking (Segal et al., 2006). Compared to measurements of knee flexion during alpine skiing, the total flexions of the laboratory measurements are comparable to the flexions measured in alpine skiing, which are measured at the inner leg (86 ± 5°). On the outer leg, the knee flexion was smaller (66 ± 4°) (Kröll et al., 2010). Other authors (Panizzolo et al., 2013, Yoneyama et al., 2000) have written that knee flexion in alpine skiing is typically between 40 and 85°. Again, this shows that the selected kinematics of the prosthetic assembly are suitable for regular two-track alpine skiing.

This study has several limitations that should be considered when interpreting the results. First, the kinematics of an artificial limb allows only planar movements. As a result, the kinematics of the legs and prosthesis were studied in the sagittal plane only, although it is well known that for quality alpine skiing, abduction/adduction and internal/external rotation are also required. However, in squats, there are also some degrees of internal/external rotation (Böhm and Senner, 2008); therefore, a future study should observe how the limitations of internal/external rotation influences the movement of a skier with an above-knee amputation when using an artificial limb with a multiple-axis prosthetic knee.

The authors are aware that the statistical methods used in this study should be applied to independent samples only. For this purpose, a sample was represented by ten randomly selected cycles out of two series and forty measured cycles. To eliminate the effect of fatigue, measurements of various additional loadings were also selected randomly; there were also at least eight-minute rest periods between each measurement. Because only one amputee was involved in the study, findings of this study should be interpreted with caution.

This study appears to be the first study that analyses above-knee prostheses made for alpine skiing on both skis. Future studies should focus also on dynamics, which can provide forces and torques in the ankle and knee joints. The results of such studies could serve to better tune prosthetic parameters (e.g., the rigidity of springs or the moment in the prosthetic knee, movement hindrance) for skiing and measurements on terrain. A comparison between single-axis and multi-axis prosthetic knees could also be useful; this comparison could analyse the advantages and/or disadvantages of each concept. Comparison of laboratory and field measurements could also describe the quality and usability of laboratory measurements. If the laboratory measurements could be proven to be adequate (i.e., comparable) with those performed in real conditions, they could help design optimal prosthetic parameters for skiers with above-knee amputation using a relatively quick and cheap process.

Conclusion

The purpose of the study was to simulate skiing in a laboratory, to analyse the flexion in ski boot, ankle and knee joints in an amputee with an above-knee amputation of leg and to compare them with his intact leg and a control group of regular skiers. In addition, the influence of additional load was analysed to simulate different regimes of skiing. It was found that the above-knee artificial limb, which was purpose-built for skiing with a built-in multi-axis knee joint that, in addition to flexion, also allows movement of the knee forwards along with virtual dorsal flexion in the ankle joint, achieved similar kinematics to those of a healthy leg; however, the angles in the ankle joint and the ski boot were found to be significantly different. It can be concluded that the above-knee artificial limb with a built-in multi-axis prosthetic knee joint resembles the kinematics of natural knee movement during alpine skiing. According to the measuring conditions used in this study, it can be assumed that the kinetics of the multi-axis prosthetic knee joint would also be similar; however, further measurements are required to confirm this hypothesis. Because the practical case for a measured subject showed that high quality skiing can be achieved with such a multi-axis purpose-built artificial limb, some major changes can be expected in the field of skiing for people with above-knee amputation in the near future.

Acknowledgements

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Key points

- The RoM in the ski boot on the side of the prosthetic leg was smaller than the RoM of the intact leg and the control group of healthy subjects.
- The RoM in the ankle joint of prosthetic leg was comparable to that of the intact leg and the control group of healthy subjects.
- The RoM in the prosthetic knee joint was greater than the RoM in the knee joint of the intact leg and smaller than that of the control group.
- The total knee flexions in the laboratory measurements were comparable with field measurements.
- Additional load affects the RoM of the ski boot, ankle and knee joints for the amputated skier in both legs. No significant influence from the additional load was found on the RoM in the control group of healthy subjects.
- The above-knee prosthesis with a multiple-axis prosthetic knee reproduces the alpine skiing kinematics of an intact leg.

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