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Design, fabrication, and preliminary results of a novel below knee prosthesis for snowboarding: A case report.

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Abstract

Snowboarding with a below-knee prosthesis is compromised by the limited rotation capabilities of the existing below-knee prostheses, which are designed for use in normal walking. Based on snowboarding range of motion analyses, a novel below-knee prosthesis was designed with the aim to achieve similar range of motions like able-bodied snowboarders. The new prosthesis allows for passive inversion/eversion, passive plantarflexion/dorsiflexion and additional 'voluntary' plantarflexion/dorsiflexion initiated by lateral or medial rotation of the upper leg and knee. A prototype was tested on a single subject, a professional snowboarder. The results indicate that snowboarding with the new prosthesis is more comparable to able-bodied snowboarding.

Keywords: Prosthetic design; prosthetic feet; rehabilitation of prostheses users; lower extremity prostheses; sports; snowboarding; bio-inspired design

1. Introduction

A prosthesis can support physically challenged people in their daily activities. The two most important factors for someone with a lower limb defect using a prosthesis are the mobility with the prosthesis and the comfort of the prosthesis in diverse daily activities. This is different for other activities like sports, because often it is not possible to practice sports at all or while practicing sports the mobility is limited by the prosthesis. A prosthesis specially designed for snowboarding can improve the comfort while snowboarding and the mobility on the slope for the people already snowboarding with a leg prosthesis. For other people it can be an encouragement to see the possibilities to perform sports with a physically challenge. Besides snowboarding the prosthesis can be employed in other similar sports, like wakeboarding or kitesurfing. In the future the prosthesis can be used for skiing or wave surfing by adjusting some parts of the prosthesis.

During snowboarding the head, arms and upper body are mainly used to initiate and end a turn whereas the lower body is active during the entire turn, requiring rotations of the foot-, ankle-, knee-, and hip-joints. Because of the

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absence of a foot and an ankle, someone with a below-knee amputation is limited in performing these motions making snowboarding more difficult. Unfortunately, existing prosthetic components do not provide the necessary passive and/or active rotation possibilities, as most of the prostheses are set with a fixed alignment. As a result, three major sub-problems can be identified:

- Due to the fixed alignment of a traditional below-knee prosthesis, the up-right posture of a person with a transtibial amputation on a snowboard differs considerably from a person without an amputation1, making snowboarding more challenging.
- Further, a certain amount of passive rotation ability within the ankle joint is important. Such a rotation is normally used in snowboarding to adapt to the different types of terrain, landing jumps and leaning into turns. The rotations at the ankle used in snowboarding are plantarflexion/dorsiflexion, inversion/eversion, and abduction/adduction [1][2]. Traditional below-knee prostheses provide no, or only to a limited amount of such rotations.
- The majority of below knee prostheses are passive, meaning that the amputee is not able to exert control over the ankle joint. However, "voluntary control" of the plantarflexion/dorsiflexion in a small range of motion would enable the snowboarder to correct the angle of the snowboard with respect to the slope, thus modulating its grip when turning.

Based on the limitations mentioned above, it was decided to design and construct a new below-knee prosthesis for snowboarding that would allow interaction between the snow-boarding person and the board similar to a person with no amputation.

2. Methods

Three phases were identified in order to develop the new below-knee prosthesis for snowboarding.

2.1. Phase 1: Design criteria

The new design is intended to approximate able-bodied ankle movement during snowboarding. Motion and force analysis of snowboarding were performed to understand snowboarding biomechanics and kinetics required for the design. The following were considered important design criteria: (a) foot angles, (b) passive degrees of freedom, (c) possibility to "voluntary" control the ankle in order to adapt to different slope angles during turning. A literature survey was used to determine the required angles [1].

With the design criteria found, a new design was conceived, inspired by the anatomy and functionality of the normal human ankle.

2.2. Phase 2:Manufacturing of prototype:

The newly designed prosthesis was manufactured.

2.3. Phase 3: Testing of the prototype in the laboratory and on a single highly professional subject.

In the laboratory the actual passive and active rotation angles achievable were measured and compared to the design criteria. Because usual 3D-motion analysis systems are not possible to be used in these circumstances (reflection of infrared light on the slope), two normal HD video cameras were used instead. Marker strips placed on the leg provided clear indications of the legs' rotation. One camera was placed in line with the subject and the other perpendicular to the subject, see Fig. 1. Video recording was performed on the three phases of a turn: the launch phase, the turn phase and the release phase for both a front- and backside turn, i.e. facing downhill and uphill respectively. The motions with the new prosthesis were analyzed and compared to the motions made with a traditional below-knee prosthesis, and those of an able-bodied snowboarder.

The measurements were taken for an able-bodied subject, a subject with a traditional below-knee prosthesis which is a carbon fiber reinforced shell, shaped as a mirrored copy of the sound leg, and the same subject with the new below-knee prosthesis discussed in this article. This subject was a highly experienced professional snowboarder and a candidate for the Olympic Winter Games before her amputation. Prior to their participation, the subjects were informed about the aims of the study and provided consent.

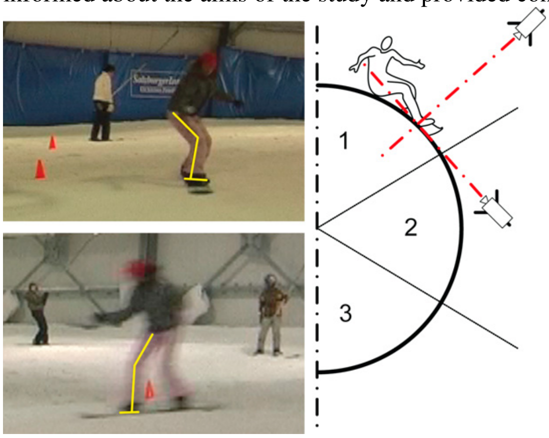

Fig. 1. the use of the ankle joint is measured with the help of two HD video cameras. Marker strips are placed on the leg to have a clear vision on rotation of the leg, shown on the left. One video camera is placed in line with the subject and the other is placed perpendicular to the subject, shown on the right.

3. Results

3.1. Biomechanical analysis

From the literature, the angles for the foot in initial stance, for the passive rotations, and for the active "voluntary" control were derived, see Fig. 2.

3.2. Bio-inspired design

The human ankle was used as inspiration for the design. The passive rotation of the below knee prosthesis can be related to the plantarflexion and dorsiflexion in the human ankle joint [3]. The active control by using supination/pronation can be related to the rotation of the subtalar joint of the human ankle, where a combination of plantarflexion/dorsiflexion and inversion/eversion resembles the motion necessary for the active control [3].

By using an outward rotation of the knees and hip, the abduction/adduction and inversion/eversion of the newly designed subtalar joint can be controlled. This joint is shaped in such a way that the abduction/adduction and inversion/eversion of the foot is coupled to plantarflexion/dorsiflexion of the foot. Thus a lateral rotation of the upper leg and knee will result in dorsiflexion of the ankle and vice versa a medial rotation of the upper leg and knee will lead to plantarflexion [4]. This method is used in able-bodied snowboarding to actively control the difference between a drifting and a carving turn.

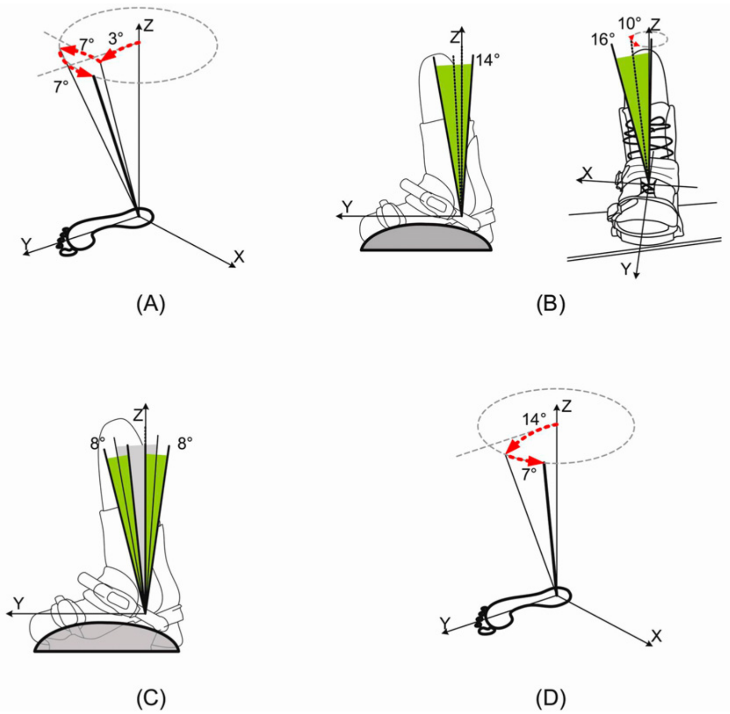

Fig. 2. results from biomechanical analysis. (A) initial setup of the ankle joint for snowboarding of the front leg. The Z-axis represents the lower leg for normal prostheses. The rotations are shown to reach the setup used for the prosthesis for snowboarding, +3° Dorsiflexion, +7° Eversion and +7° Adduction. (B) passive rotational freedom within the ankle joint for snowboarding. (Left) The passive rotation around the ankle joint, leading to plantarflexion/dorsiflexion. A 14° range of motion is required, which is evenly divided around the initial setup of the ankle indicated by the dotted line. (Right) The passive rotation around the subtalar joint, leading to adduction/abduction and inversion/ eversion. A 20° range of motion is required for the inversion/eversion, which is evenly divided around the initial setup of the ankle indicated by the dotted line. A 10° range of motion is required for the abduction/ adduction, which is evenly divided around the initial setup of the ankle indicated by the dotted line. (C) active control of the plantarflexion and dorsiflexion in the ankle joint. An 8° range of motion is required, which is evenly divided around the end of the passive range of motion discussed in the previous part. This active range of motion is used both at the end of the passive range of motion in the frontside and backside turn. (D) initial setup of the ankle joint for snowboarding of the rear leg. The Z-axis represents the lower leg for normal prostheses. The rotations are shown to reach the setup used for the prosthesis for snowboarding, +14° Dorsiflexion and +7° Adduction.

The orientation of the lower leg with respect to the foot can be analyzed in the transverse plane, see Fig. 3A. Using Euler rotation matrices to calculate the rotation of the lower leg around the subtalar joint for a human ankle, Fig. 3B, leads to approximately the same orientation of the oblique solid black lines in Fig. 3A, representing respectively the active rotation of the below knee prosthesis and the subtalar joint rotation in the human ankle.

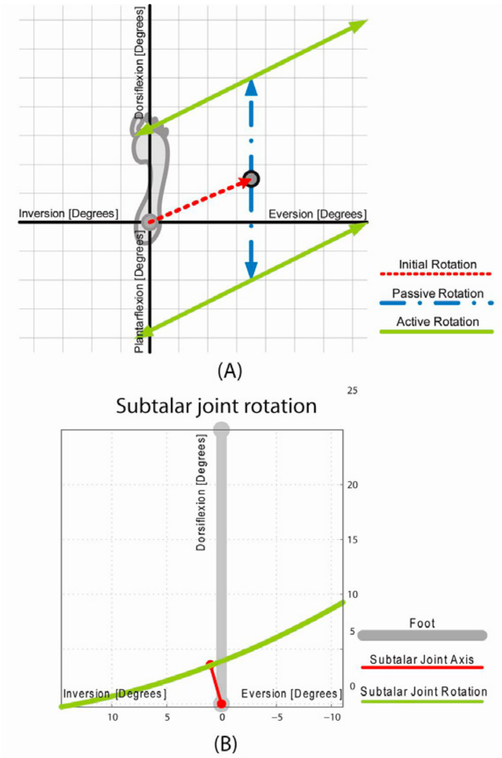

Fig. 3. (A) the superior view of the foot. The orientation of the lower leg with respect to the foot is shown in degrees. Within this figure the summation of the movement of the ankle joint in the prosthesis is shown. The dotted line indicates the transfer from a normal stance of the ankle to the initial stance for snowboarding, where the +3° dorsiflexion and +7° eversion is implemented. The dashed line indicates the passive rotation around the ankle joint earlier discussed, which is +7° plantarflexion and +7° dorsiflexion around the initial stance. The solid lines indicate the rotations of the active control at the end of the passive rotation. Here the combination of the 8° plantarflexion/dorsiflexion, the desired active motion, is combined with the +16° inversion/eversion, the passive motion necessary. (B) the rotation around the subtalar joint axis, shown in the superior view. The bold grey line indicates the foot, the grey line the subtalar joint axis and the black line the rotation of the leg around the subtalar joint axis.

3.3. Prototype

The bio-inspired concept is transformed into a prototype design using standard modular prosthetic components where possible: A Trulife, adjustable clamp adapter (titanium, SCA225) was used for the connection of the prototype to the socket. A slight modification was made to a standard keel of a Seattle carbon lightfoot (SCF, Trulife) to enable its connection to the remainder of the design. Materials for the design specific parts were aluminium, stainless steel and bronze chosen due to their price, specific strengths and machining properties.

In Fig. 4A the passive rotation of the design is shown, a rotation around the ‘ankle joint’ reacting to external forces only. The “voluntary” rotation, shown in Fig. 4B, is a rotation around the newly-created subtalar joint. Voluntary lateral or medial rotation of the upper leg and knee initiates this rotation.

The main challenge in the design was the oblique angle of the subtalar joint. As a consequence many different adjourning parts have faces which are not perpendicular to one another. The overall design and construction of the prosthesis was straight forward. No very high precision and tolerances were needed; the main bearings of the ankle axis and the subtalar axis were with an h7/H7 fit the tightest in tolerance.

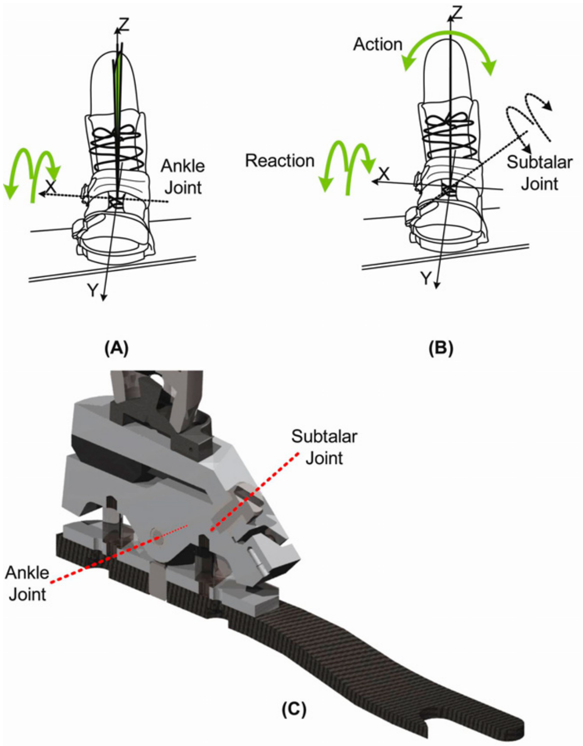

Fig. 4. (A) the grey shaded area in the XZ-plane indicates the passive plantarflexion/dorsiflexion option of the new prosthesis. (B) active plantarflexion/dorsiflexion is made possible by the incorporation of a 'subtalar joint' in the new prosthesis. This joint is a normal hinge joint which axis of rotation points into the negative X-, and into the positive Y- and Z-direction. Voluntary lateral or medial rotation of the upper leg and knee (the action) initiates a rotation around the 'subtalar joint' which subsequently results in plantarflexion/dorsiflexion of the ankle. (C) A cross sectional drawing of the ankle. The axis for the ankle joint and the subtalar joint are clearly visible.

In Fig. 5 the final prototype is shown after construction. The total mass of the foot in combination with the socket is 1.5 kg.

(A) (B)

Fig. 5. final prototype after construction and assembly. (A) final prototype and; (B) final prototype connected to the socket and residual limb.

3.4. Test results

The laboratory tests showed the rotations defined in the design criteria were met in the prototype.

A field test with a single subject was performed to obtain a first impression of the qualities of the new design. The angles measured are and plotted in a graph, see Fig. 6. The standard deviation is left out of the graphs, for increased readability. The new designed prosthesis achieved similar degrees for ankle dorsiflexion and ankle eversion as those seen for an able-bodied person see Fig. 6A. The test subject with the below-knee defect was very pleased with the new prosthesis design. It enabled improved control over the board: "snowboarding with the new prosthesis is like it was before the amputation."

4. Discussion

In the prostheses currently used for snowboarding the ankle plantarflexion/dorsiflexion has a smaller range of motion than the one achieved with the new design. This smaller range of motion will lead to an asymmetrical turning behaviour, and thus reduces controllability. The increased plantarflexion/dorsiflexion of the new design indicates the extended use of passive rotation.

Lateral rotation of the upper leg and knee will result in pronation of the subtalar joint (used for backside turns), and the medial rotation of the upper leg and knee will result in supination of the subtalar joint (used for frontside turns). The inversion/eversion of the ankle joint during snowboarding indicates the use of the active rotation of the subtalar joint, see Fig. 6B. The able-bodied subject and the subject with the new prosthesis show an increased similarity in active dorsiflexion/plantarflexion indicating that they may use similar techniques to achieve this rotation.

The able-bodied subject, the subject with the new prosthesis and the subject with the old prosthesis have a correlated knee flexion/extension, see Fig. 6C. However, the range of knee flexion/extension of the subject with the new prosthesis is larger compared to the range of knee flexion/extension of the subject with the currently used below-knee prostheses and has more resemblance with the range of knee flexion/extension of the able-bodied subject.

Measuring joint angles with video cameras has a limited accuracy. The measurements in this study are used for relative comparison of the joint angles in the different subjects during snowboarding. Because of this limitation, and given the single subject trial, it is difficult to generalize the findings.

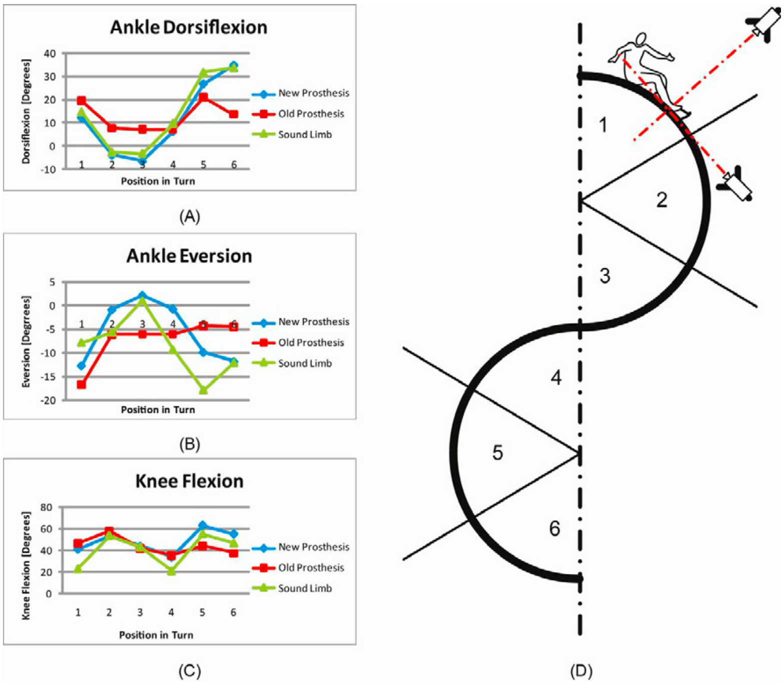

Fig. 6. (A) the plantarflexion/dorsiflexion of the ankle; (B) the inversion/eversion of the ankle; (C) the flexion/extension of the knee and; (D) the measurements positions in the turn, correlating to the graphs.

5. Concluding remarks

The overall goal of this R&D project was to improve mobility and control when snowboarding with a below-knee prosthesis. In order to reach this overall goal sub-problems were solved.

When using the new design, the orientation of the lower leg with respect to the foot resulted into a standing posture which was symmetrical, taking the sagittal plane as reference. The ability to dorsiflex, evert and abduct the new prosthetic design leads to a stance natural for snowboarding. Added passive rotation in the ankle joint, show a clear change in the plantarflexion/dorsiflexion rotation during the turns for the subject with the new prosthesis, which is comparable to the range of motion used by the able-bodied subject. The “voluntary” rotation of the new subtalar joint enabled additional control of the supination/pronation angle and resulted in a drifting or carving turn. Its design was derived from the use of the subtalar joint for able-bodied snowboarders. The subject had been snowboarding before the amputation, which made it possible to retrieve this technique during the first descents. The measurements of the inversion/eversion of the lower leg compared to the foot show an increasing use of this rotation for the subject with the new below knee prosthesis when compared to the subject with the traditional below-knee prosthesis. This increased use of inversion/eversion of the lower leg with respect to the foot gives an indication for the use of this new additional joint.

On a subjective basis it was noted that the subject was very enthusiastic about the additional rotation possibilities, allowing the ankle to adjust to turns. In particular, the ability to control the subtalar joint and thus to increase the pressure on the snowboard boarder while turning seems to make snowboarding like it used to be.

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