A novel below-knee prosthesis for snowboarding

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 of allowing a disabled snowboarder to achieve a similar range of motions as able-bodied colleagues.

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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 mobility and comfort 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 comfort and mobility on the slope for people already snowboarding with a leg prosthesis. For other people it can be an encouragement to see the possibilities of performing sports with a physical challenge. Such a prosthesis can also be employed in similar sports, like wakeboarding or kitesurfing. In future, the prosthesis may be used for skiing or wave surfing after adjustment of 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 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 required 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 amputation [1], making snowboarding more challenging.
- Further, a certain amount of passive rotation ability within the ankle joint is important. Such a rotation is normally used by snowboarders in adapting to the different types of terrain, in landing jumps and when leaning into turns. The rotations at the ankle used in

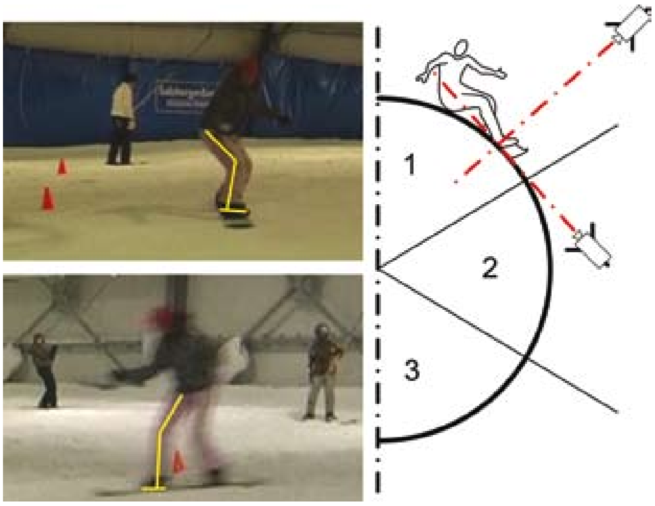

Figure 1. The use of the ankle joint was measured with the help of two HD video cameras. Marker strips were placed on the leg to have a clear vision on rotation of the leg, as shown on the left. One video camera was placed in line with the subject, the other perpendicular to the subject.

snowboarding are plantarflexion/dorsiflexion (movement of the foot downwards/upwards), inversion/eversion (twisting movement of the foot inward/outward), and abduction/adduction (movement of the foot away from/towards the center line of the body) [1] [2] [3]. Traditional below-knee prostheses do not, or only to a limited amount, provide 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 these limitations, it was decided to design and construct a new below-knee prosthesis for snowboarding that would allow “near-normal” interaction between person and board.

Methods

The new design is intended to approximate able-bodied ankle movement during snowboarding. Motion and force analysis 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, and (c) possibility to ‘voluntarily’ control the ankle in order to adapt to different slope angles during turning. A literature survey was used to determine the required angles. With the criteria found, a new design was conceived, inspired by the anatomy and functionality of the normal human ankle.

A prototype of the newly designed prosthesis was manufactured and subsequently tested.
In the laboratory, the actual passive and active rotation angles achievable were measured and compared to the design criteria. For field tests the usual 3D motion analysis systems could not be used due to the reflection of infrared light on the slope. Therefore, two normal HD video cameras were used instead; see Figure 1.Video recording was performed on the three phases of a turn: the launch, the turn and the release, for both a front- and a backside turn, i.e. facing down- and uphill, respectively. The motions with the new prosthesis were analysed and compared to the motions made with a traditional below-knee prosthesis, and those of an able-bodied snowboarder. The measurements were performed for an able-bodied subject, a subject with a traditional below-knee prosthesis, which is a carbon fibre reinforced shell, shaped as a mirrored copy of the sound leg, and the same subject with the new below-knee prosthesis discussed here. This subject was a highly 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 they provided consent.

Results

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 Figure 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 [4]. The active control by using supination/pronation (an outward/inward roll of the foot, actually a combination of inversion, plantarflexion and adduction, or eversion, dorsiflexion and abduction, respectively [3]) 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 required for the active control [4].
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

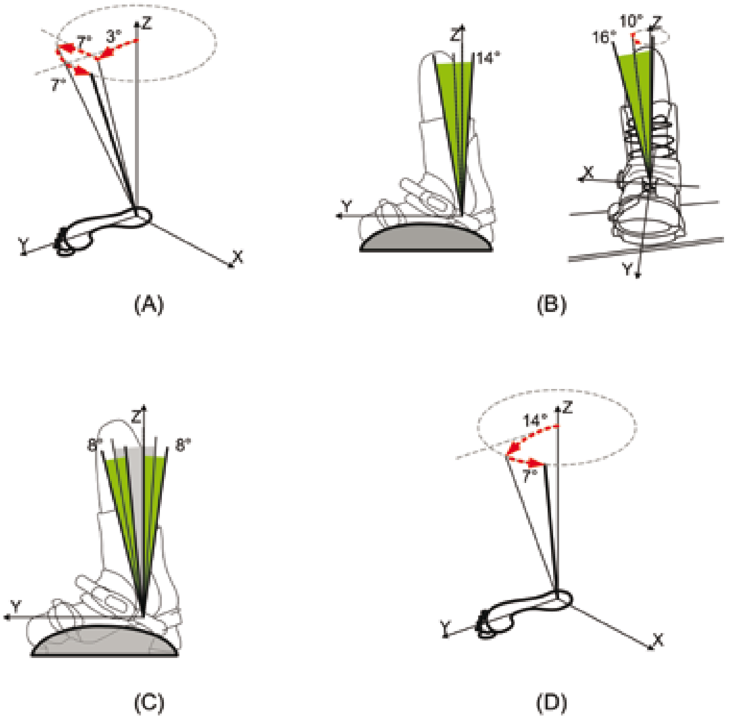

Figure 2. Results from biomechanical analysis.

(A) Initial set-up 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 set-up used for the prosthesis for snowboarding, +3° dorsiflexion, +7° eversion and +7° adduction.

(B) Passive rotational freedom within the ankle joint for snowboarding.
On the left, the passive rotation around the ankle joint, leading to plantarflexion/dorsiflexion, is shown. A 14° range of motion is required, which is evenly divided around the initial set-up of the ankle indicated by the dotted line.
On the right, the passive rotation around the subtalar joint, leading to adduction/abduction and inversion/eversion. A 16° range of motion is required for the inversion/eversion, which is evenly divided around the initial set-up 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 set-up 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 at the end of the passive range of motion in the frontside as well as the backside turn.

(D) Initial set-up 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 set-up used for the prosthesis for snowboarding, +14° dorsiflexion and +7° adduction.

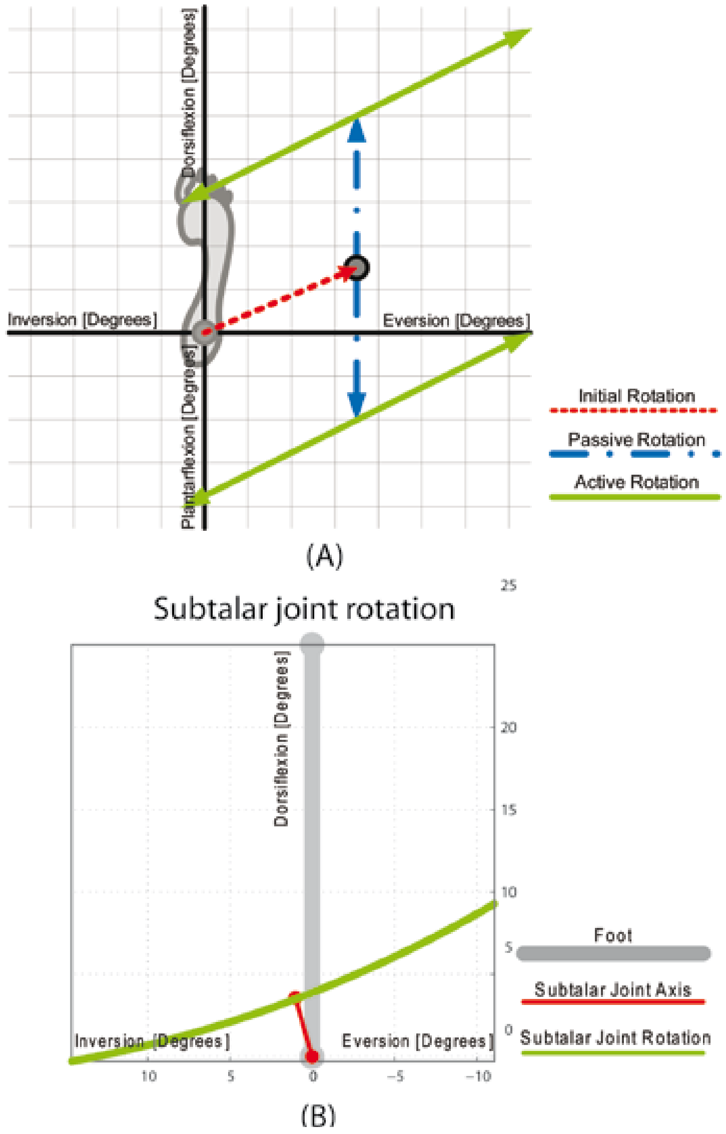

Figure 3. Rotations in the bio-inspired design.

(A) 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 red 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 blue line indicates the passive rotation around the ankle joint, which was discussed earlier, +7° plantarflexion and +7° dorsiflexion around the initial stance. The green 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 required.

(B) The rotation around the subtalar joint axis, shown in superior view. The bold grey line indicates the foot, the red line the subtalar joint axis and the green line the rotation of the leg around this axis.

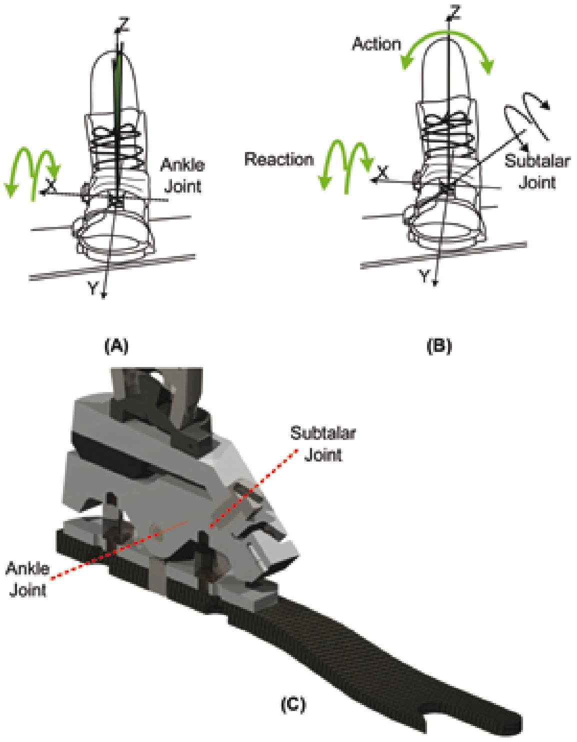

Figure 4. The design of the new prosthesis.

(A) The green shaded area in the XZ-plane indicates the passive plantarflexion/dorsiflexion option.

(B) Active plantarflexion/dorsiflexion is made possible by the incorporation of a ‘subtalar joint’. This joint is a normal hinge joint that has its axis of rotation pointing into the negative X-, the positive Y- and the positive 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) Cross-sectional drawing of the ankle. The axes for the ankle joint and the subtalar joint are clearly visible.

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 (away from the center line of the body) of the upper leg and knee will result in dorsiflexion of the ankle and vice versa a medial rotation (towards the center line of the body) of the upper leg and knee will lead to plantarflexion [5]. This method is used by able-bodied snowboarders to actively control the difference between a drifting and a carving turn.
The orientation of the lower leg with respect to the foot can be analysed in the transverse plane, see Figure 3A. Using Euler rotation matrices to calculate the rotation of the lower leg around the subtalar joint for a human ankle, Figure 3B, leads to approximately the same orientation of the oblique solid black lines in Figure 3A, representing the active rotation of the below-knee prosthesis and the subtalar joint rotation in the human ankle, respectively.

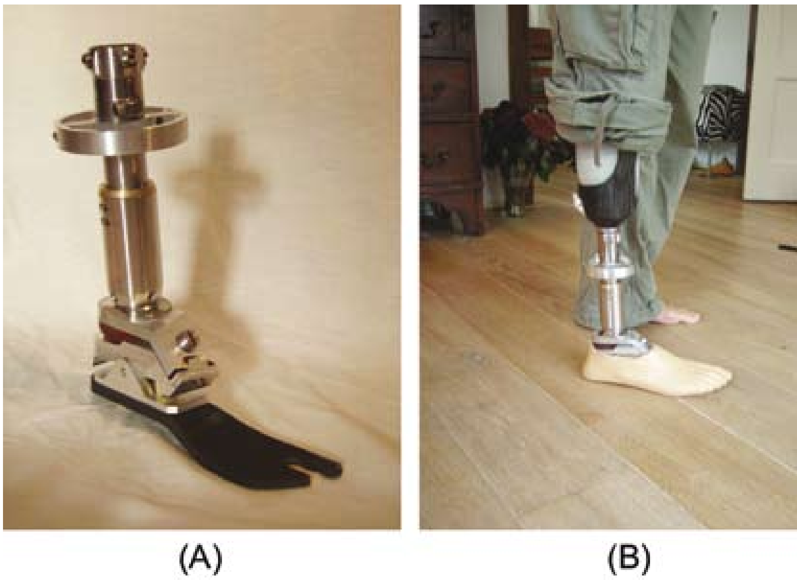

Figure 5. Final prototype.
(A) After construction and assembly.
(B) Connected to the socket and residual limb.

Prototype

The bio-inspired concept was 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, selected because of their price, specific strengths and machining properties.

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

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 measured angles are plotted in a graph, see Figure 6 (the standard deviation is left out for readability). The new prosthesis achieved similar angles for ankle dorsiflexion and ankle eversion as those seen for an able-bodied person, see Figure 6A. The test subject with the below-knee defect was very pleased with the new prosthesis design, as it enabled improved control over the board: “Snowboarding with the new prosthesis is like it was before the amputation.”

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. A smaller range of motion will lead to an asymmetrical turning behaviour, thus reducing 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 Figure 6B. The able-bodied subject and the subject with the new prosthesis show an increased

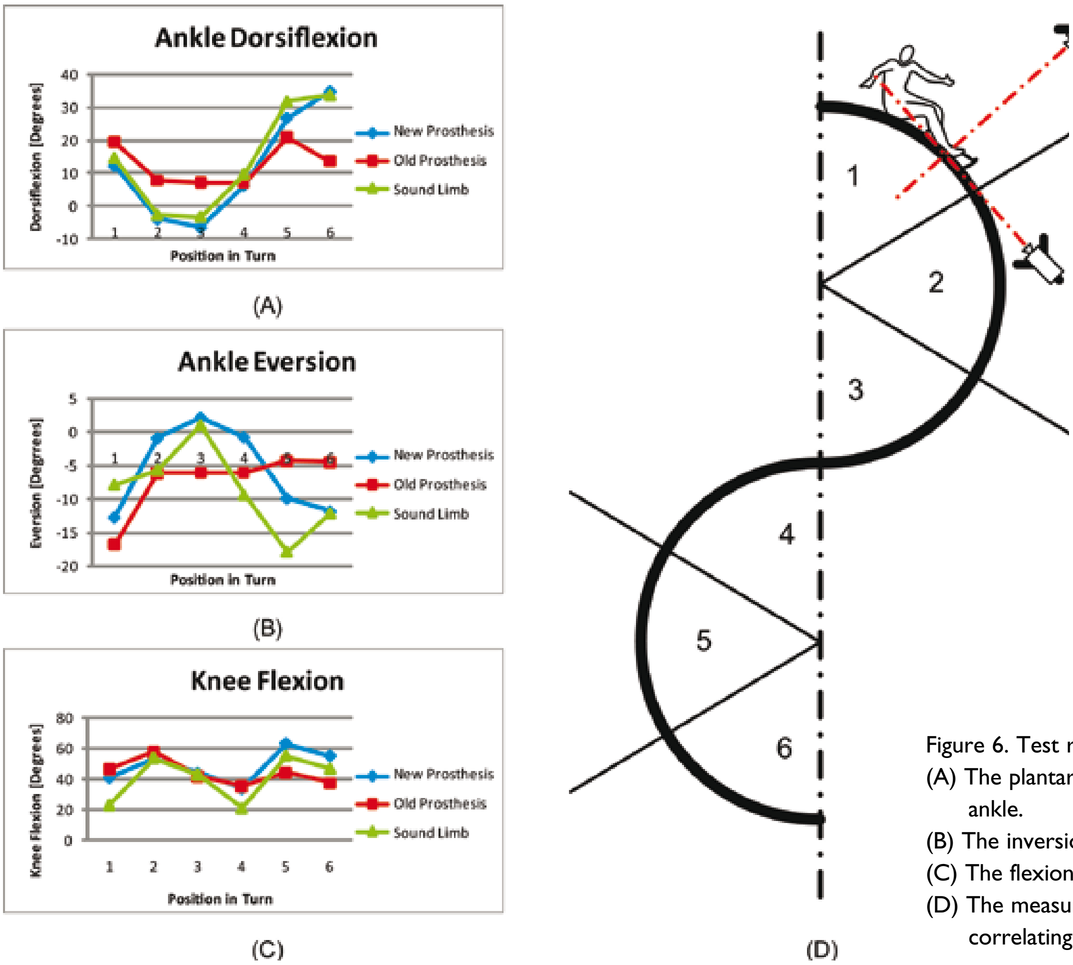

Figure 6. Test results.
(A) The plantarflexion/dorsiflexion of the ankle.
(B) The inversion/eversion of the ankle.
(C) The flexion/extension of the knee.
(D) The measurement positions in the turn, correlating to the graphs.

similarity in active dorsiflexion/plantarflexion indicating that they may use similar techniques to achieve this rotation.

All subjects have a correlated knee flexion/extension, see Figure 6C. However, the range of knee flexion/extension of the subject with the new prosthesis is larger than that of the subject with the currently used below-knee prosthesis and shows more resemblance with that of the able-bodied subject.

It must be noted that measurement of joint angles with video cameras has limited accuracy, but can be used, however, for comparison purposes, as was done in this study. Because of this limitation, and given the single-subject trial, it is difficult to generalise the findings.

Concluding remarks

The overall goal of this R&D project was to improve mobility and control when snowboarding with a below-knee prosthesis. The orientation of the lower leg with respect to the foot resulted in 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 that is natural for snowboarding. Added passive rotation in the ankle joint shows 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 test 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 with respect 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 finding 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 while turning seems to make snowboarding like it used to be.

Authors’ note

This article is an abbreviated version of the article “Design, fabrication, and preliminary results of a novel below-knee prosthesis for snowboarding: A case report”, as published in *Prosthetics and Orthotics International*, September 2009, 33(3): 272-283, doi: 10.1080/03093640903089576.

The work described here was performed within the BioMechanical Engineering Group at Delft University of Technology (DUT), Delft, the Netherlands. The group focuses on human-machine interaction, as approached from many different angles, such as rehabilitation aids (upper-limb prosthetics) and, more recently, prosthetics in sports.

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Dick Plettenburg received his PhD degree in Mechanical Engineering Design from DUT. He is currently an assistant professor, heading the Delft Institute of Prosthetics and Orthotics.

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Information

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