

Development of Prosthetic Knee for Alpine Skiing

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Above-knee amputation significantly reduces the amputee's mobility and physical condition that can be built up through training or other sports activities. Alpine skiing is one of them. This paper deals with an above-knee prosthesis, which provides better kinematics of the leg structure. Imitating the kinematics of the human body, we looked for the kinematics of a system that comes closest to imitating natural movement and replace the missing limb to the highest possible degree. Based on the analysis of human leg kinematics and entire human mass system dynamics, a prototype for a special multi-axis prosthetic knee was developed. Measurements of leg movement during skiing were performed, which served as a basis for the concept. The concept was verified by kinematics, dynamics and strength analysis, and a complete geometric model was made. The concept was then verified on a working prototype, tested on a ski slope.

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0 INTRODUCTION

The number of lower limb amputations has been significantly increasing in recent years [1]. Accidents result in an increase of amputations among young people who attempt to integrate into everyday life as much as possible. In order to be able to perform basic life functions, such as walking, there are many aids available; from simple and low-cost ones to more sophisticated ones, allowing broader application and comfort, but of a much higher price-bracket [2].

As soon as the threshold of basic and vital functions is crossed, it becomes apparent that in the area of aids for other activities, sporting ones in particular, there is a lot of room for new products [3]. Given the fact that we have been working with an above-the-knee amputee, who was an active skier before the injury and who can therefore provide direct testing of equipment, we decided to focus primarily on the area of alpine skiing.

The so-called three-track skiing is the most frequently used ski method by above-the-knee amputees [4] and [5]. Together with a normal ski on the sound leg, special poles (outriggers) with a flip-up ski attached to the bottom are used to provide aid in balancing. An example is shown in Fig. 1.



Fig. 1. Three-track skiing – skiing on the sound leg with the assistance of two specially designed poles

In addition to three-track skiing for above-the-knee amputees, a few varieties of above knee prostheses have been developed in recent years for regular, two-track skiing [6] and [7]. Fig. 2 shows an example of an above-knee prosthesis, incorporating the XT9 prosthetic knee, produced by the US company Symbiotech [8].

Practical use of the particular prosthesis, shown in Fig. 2 revealed that it fails to provide the optimum movements, required for quality alpine skiing. Tests showed that in combination with an ordinary ski boot this prosthesis does not allow

enough forward movement of the knee, which moves the gravity centre of the body backwards. This results in the skier losing dynamic balance and control of the skis (Fig. 3).



Fig. 2. Above-knee prosthesis for alpine skiing with the XT9 prosthetic knee



Fig. 3. Kinematics of above-knee prosthesis for alpine skiing with the XT9 prosthetic knee

The paper presents the development of a prosthetic knee as the key element of an above-knee prosthesis for alpine skiing. In doing so, we will use the problems observed above as a basis and try to eliminate them. The prosthetic knee is of particular importance for skiing and the kinematics of human structure because skiing and sports activities in general require the dynamics of the human body as the key element of motor skills [9].

The prosthetic knee is connected upwards to the body via the prosthesis socket and stump. Downwards, the prosthetic knee is connected via the tubular adapter to the prosthetic foot and further down to the ski boot [10]. Each of the elements has its own function, forming a unit together with the others. An above-knee prosthesis in an assembly is shown in Fig. 4.

In developing a new prosthetic knee, the theory of design and development process based

on the idea that technical systems should come closest to imitating natural processes and should have a minimum effect on the environment [11] and [12], was followed. To achieve maximum quality of the defined natural process that the structure of the human body deals with in skiing, first typical human skiing motion was recorded. To facilitate data acquisition, a purpose-built test area, shown in Fig. 5 was built, where the kinematics of the whole human structure was measured, particularly the leg part during the skiing process of an able-bodied individual. The measurement results were used as the basis for a special multi-axis prosthetic knee concept.



Fig. 4. Above-knee prosthesis assembly; 1 – prosthesis socket, 2 – prosthetic knee, 3 – tubular adapter, 4 – prosthetic foot

A mechanism was designed on the basis of the analysis of the skier's motion, which was then compared to the measurement results. Varying the locations of the prosthetic knee's kinematic system axes, the kinematics of a sound knee in skiing were approximated.

Having researched and recorded behaviour during skiing, it was concluded that in addition to kinematics, dynamics. Ordinary above-knee walking prostheses have the basic function of knee contracture in the swing phase, followed by system stabilisation at landing [13] and [14]. Contrary to this, in the knee-contracture phase skiing requires adequate force upon the ski and surface in order to be able to perform the function of guiding the ski. Due to this additional function required for skiing, it is necessary to equip the knee prosthesis system with an energy accumulation system, so that some force returns to the surface – the ski in this case – during the knee contracture phase [15].

On the basis of the recorded states of real skiing motions, a geometric knee-prosthesis

model was made. Defining mechanism fulcrums, we tried to improve it in such a way as to come closest to natural movement. This was followed by building a virtual model of the prosthetic knee, which then required verification of its strength suitability. The virtual model was strength tested at maximum loads, specified on the basis of the kinetic analysis of the mechanism.

For higher quality reasons, a prototype was built and tested on a ski slope.

1 LEG KINEMATICS MEASUREMENT IN SKIING

According to the method [16], the development of each new product first requires recognising the natural process, which the new product should provide in the form of a technical system. To this end, a special test area was arranged which in the first place provided forces exerted by the skier on the surface, which is basically a simulation of increased forces when making a turn [17]. Together with the measurement of forces, the kinematics of human structure in the leg area was also measured. It allowed us to recognise the key condition of the kinematics of the structure in connection with forces acting on the structure of the human body.

1.1 Test Area and Performance of Measurements

For some loads on the lower (leg) part of human structure, a test area provides fully contactless optical tracking of skier motion in space. The test area concept is shown in Fig. 5. Skis are attached to an AMTI tensiometric plate, which measures loads on the surface. Other forces that appear during skiing were simulated by means of a rope system, attached from the skier's lower body to vertically guided weights. Data were captured by a system, based on a 2-D image capturing of control points movement on two planes (Fig. 6). Control points positions were captured using two high speed cameras CASIO EXILIM F-1, positioned at an angle of 90° relative to each other. Using image analysis of each camera and space calibration, the location of control points in space was determined. The test track enabled tracking the size and direction of the extra load, which significantly affected the quality of the executed measurements.

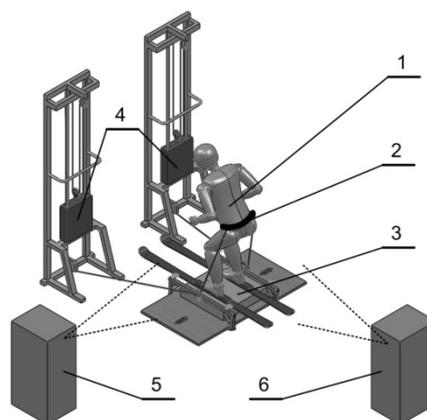


Fig. 5. Test area concept; 1-skier, 2-extra loads transfer system, 3-tensiometric plate, 4-weights, 5-data capturing system from the side, 6-data capturing system from behind

Four measurements of human body kinematics were executed at different extra loads, depending on the skier's body weight (BW).

- A – no extra load,
- B – extra load 1/3 BW,
- C – extra load 2/3 BW,
- D – extra load 1 BW.

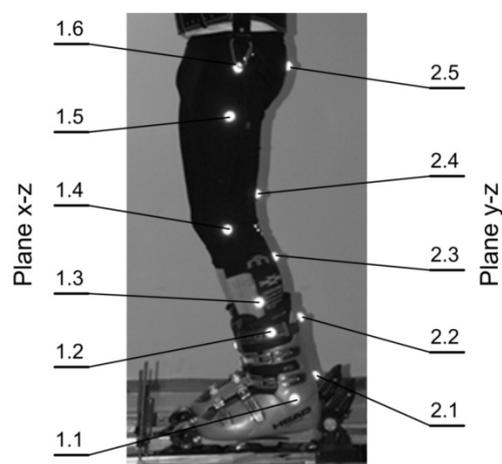


Fig. 6. Location of control points for the kinematic analysis of skier's leg; 1.1–boot-ankle left, 1.2–boot-upper left, 1.3–lower leg left, 1.4–knee left, 1.5–thigh left, 1.6–pelvis left, 2.1–boot-centre rear, 2.2–boot-upper rear, 2.3–lower leg rear, 2.4–thigh rear, 2.5–pelvis rear

Capturing data from two orthogonal directions – from the side (Fig. 6, 1.1. to 1.6) and

from behind (Fig. 6, 2.1 to 2.5), a description of leg kinematics in space was achieved. Fig. 7 shows the range of measurements and the choice of coordinate system. Measurement results for each direction are presented below.

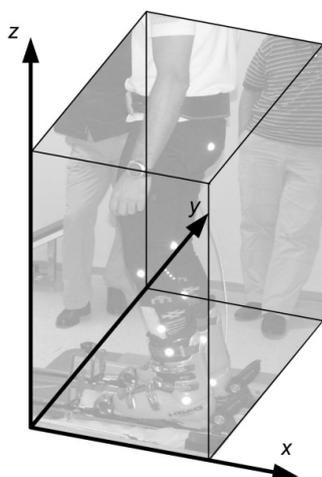


Fig. 7. Space calibration and setting up a coordinate system

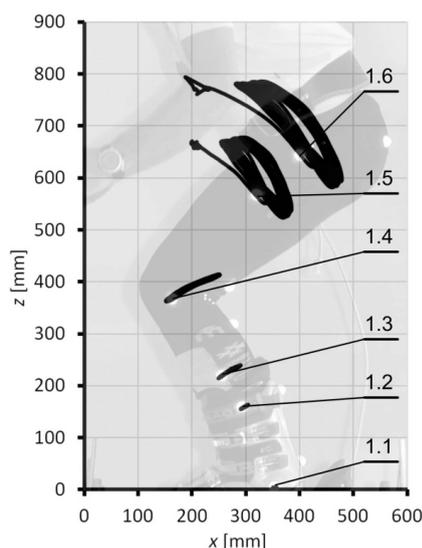


Fig. 8. Measurement result for the kinematics with no extra load – x-z plane

1.2 Measurement Results of the Kinematics of Human Structure

Coordinates of individual points were determined by means of space calibration and image analysis. Figs. 8 and 9 show the movement

of individual control points, representing human structure in individual planes.

Fig. 10 shows comparison between measurement results at different extra loads. For better transparency reasons, each measurement is presented by a single cycle, simulating one turn. The results clearly show that knee movement increases with increasing extra loads. The reason for this is in the stiffness of the ski boot, which restricts forward movement (displacement) of the foot.

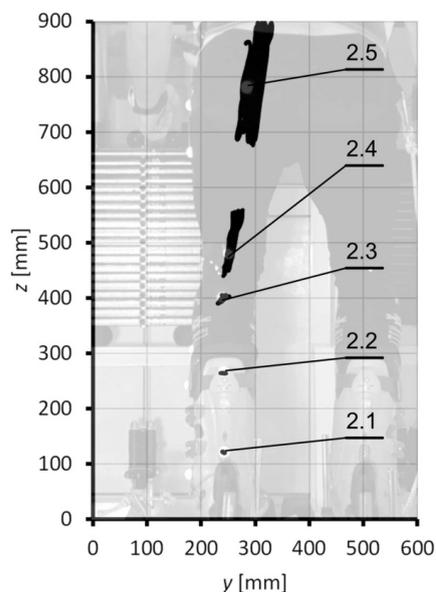


Fig. 9. Measurement result for the kinematics with no extra load – y-z plane

2 MULTI-AXIS MECHANISM CONCEPT AND KINEMATIC ANALYSIS

Developing the prosthetic knee concept, the principle of making a simple and low-cost prosthesis, which would at the same time closely imitate natural movement, was followed. The solution was found in a multi-axis prosthetic knee which would, independently of the ski boot, provide the kinematics similar to that in the sound leg. The prosthetic knee concept is shown in Fig. 11. It consists of a lower plate, to which a tubular adapter is attached, followed by a prosthetic foot. The prosthesis socket is attached to the upper plate. The plates are connected by arms that provide the necessary movement in the horizontal and vertical directions relative to the turn (contracture) of the

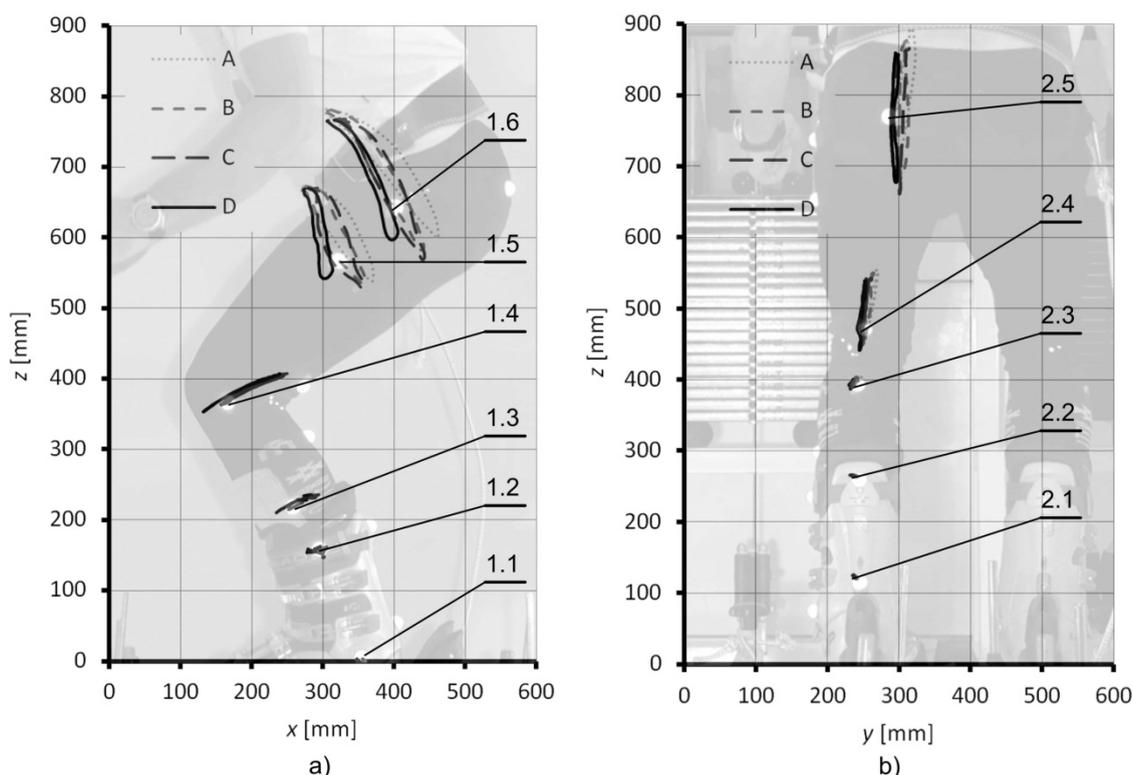


Fig. 10. Comparison between measurement results at different extra loads; a) x-z plane, b) y-z plane
 A – no extra load, B – extra load 1/3BW, C – extra load 2/3BW, D – extra load 1BW

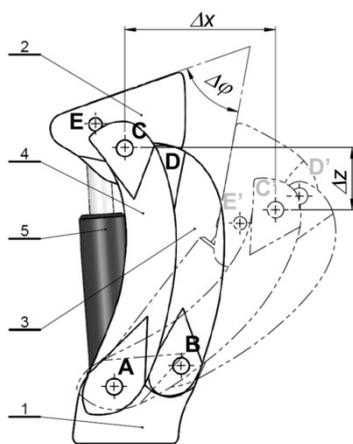


Fig. 11. Multi-axis prosthetic knee concept:
 1-lower plate, 2-upper plate, 3-front arm,
 4-rear arm, 5-shock absorber, $\Delta\phi$ -knee turn
 (contracture), Δx -horizontal movement,
 Δz -vertical movement; A, B, C, D and E –
 mechanism axes

knee. The dynamics of the mechanism is provided by a corresponding pneumatic shock absorber and coil spring system.

A kinematic analysis of the mechanism was carried out for the presented multi-axis prosthetic knee. Trajectories of individual axes were calculated by means of which the movement of the upper part of the prosthetic knee, relative to the lower one, was determined. Fig. 12 shows movements of the pivot points of the upper part. Point (axis) C represents the control point for the comparison between the kinematics of a sound knee and a prosthetic one.

Fig. 13 shows a comparison between the measurement results of the control point movement on the knee (control point 1.4 in Fig. 6) at different loads, and the results of the kinematic analysis of the prosthetic knee concept (C in Figs. 11 and 12). Fig. 13a shows a comparison between movements in the horizontal (x) direction, and

Fig. 13b in the vertical direction (z), relative to the angle of knee turn (contracture).

3 VIRTUAL PROSTHETIC KNEE MODEL AND STRENGTH ANALYSIS

Judging by the kinematic analysis results (Fig. 12) and comparing measurement results (Fig. 13) the selected concept is deemed suitable. The next step in the development of the prosthetic knee was building a virtual model and performing the strength test.

One of the structure's key elements is also the combination of a pneumatic shock absorber and a coil spring, which provides suitable stiffness of the knee assembly and thus load transfer from the skier onto the surface. To this end, we tested several combinations of pneumatic shock absorbers and coil springs. The choice of the most suitable combination mostly depends on the user's psychophysical and morphological characteristics, skiing technique and skills. The structure is designed in such a way that it allows simple changes of combinations and fine tuning, depending on the user's requirements and preferences.

The strength analysis of prosthetic knee's virtual model structure was performed for the

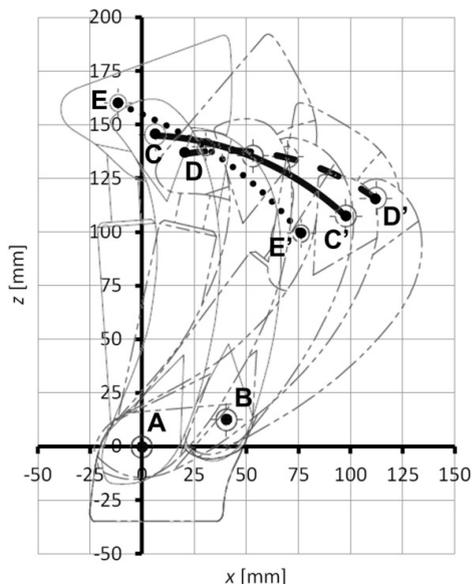


Fig. 12. Results of kinematic analysis of the mechanism

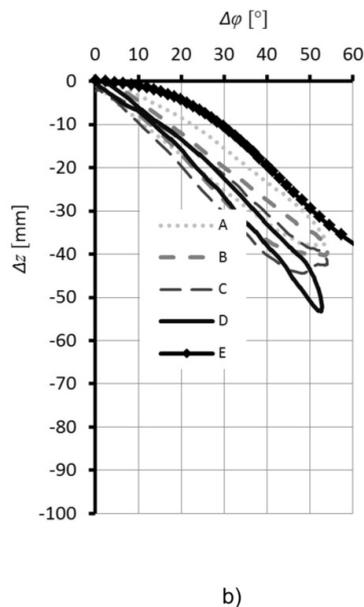
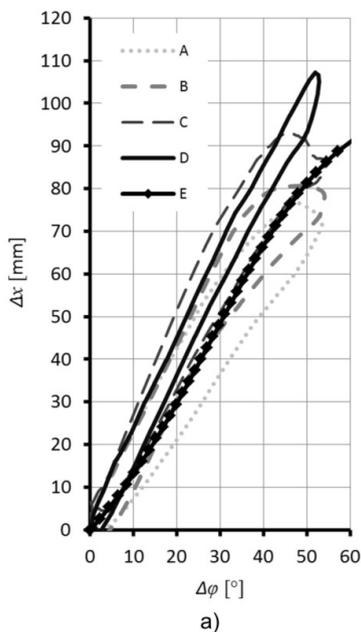


Fig. 13. Comparison between measurements and simulation of control point movement on the knee, depending on knee contracture: a) horizontal direction (x) movement, b) vertical direction (z) movement; A, B, C and D curves - control point 1.4 measurement (Fig. 5) at different loads, curve E - control point C simulation (Fig. 10) on the prosthetic knee concept

strongest pneumatic shock absorber ($F = 2,200 \text{ N}$) and coil spring (81 N/mm constant) combination. Using the kinetic analysis of the selected mechanism, forces in specific points of the mechanism were determined. These forces served as a basis for the strength analysis of particular critical elements of the structure.

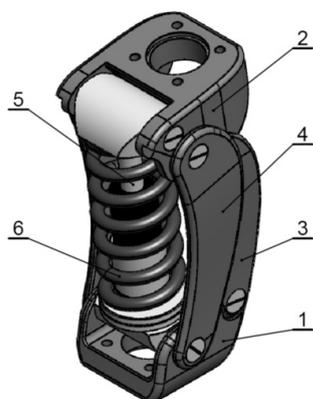


Fig. 14. Virtual model of prosthetic knee: 1-lower part, 2-upper part, 3-connecting rod front, 4-connecting rod rear, 5-shock absorber, 6 coil spring

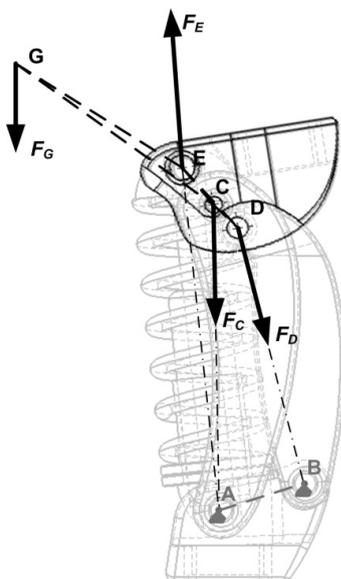


Fig. 15. Prosthetic knee model for kinetic analysis: A, B, C, D and E represent mechanism axes, G – external force point of application, F_G – external force, F_E – joint force of coil and shock absorber, F_C and F_D – forces in connecting rods

Fig. 15 shows a kinetic model of the prosthetic knee. Points A, B, C, D and E represent the mechanism axes. Point G represents the external force point of application, located at the far lower part of the prosthesis socket. Force F_E represents the joint force of the coil and the shock absorber. Force F_G represents the external force, required for knee contracture. The size of forces F_C in F_D was calculated by means of balance equations.

Analysis results and sizes of forces as a function of knee contracture angle are shown in Fig. 16.

Strength calculation of prosthetic knee elements in Fig. 14 was performed by means of the finite elements method (SolidWorks 2010). Individual elements were checked separately, taking account of the largest forces that appear at contracture.

The material of choice was aluminium alloy AlMg4,5Mn (EN AW-5083).

- elastic modulus: $71\,000 \text{ N/mm}^2$,
- poisson number: 0.33,
- cone module: $2\,640 \text{ N/mm}^2$
- material density: $2\,660 \text{ kg/m}^3$,
- tensile strength: $275 - 350 \text{ N/mm}^2$,
- yield strength: $125 - 190 \text{ N/mm}^2$.

Strength analysis showed appropriateness of the structure. Figs. 17 and 18 show the tension condition of prosthetic knee rods as the most stressed elements of the structure when they are under maximum load.

Table 1. Loads on the front connecting rod

Turn	Point B	Point D
$\Delta\varphi$	$F_D/2$	$F_D/2$
50.23°	2,019 N	2,019 N

Table 2. Loads on the rear connecting rod

Turn	Point A	Point C
$\Delta\varphi$	$F_C/2$	$F_C/2$
81.11°	2,387 N	2,387 N

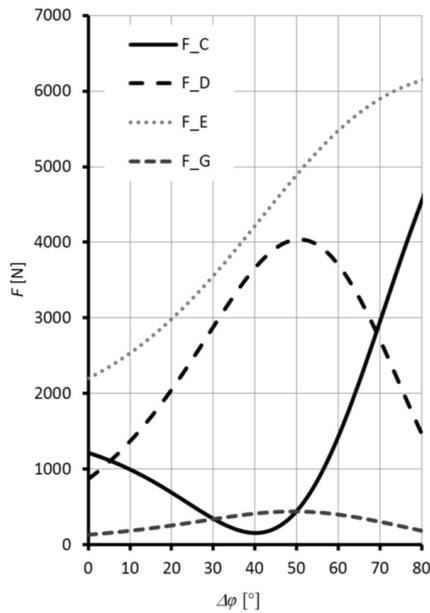


Fig. 16. Results of kinetic analysis of prosthetic knee for a selected combination of coil and pneumatic shock absorber; F_C , F_D , F_E and F_G – forces in individual points of mechanism

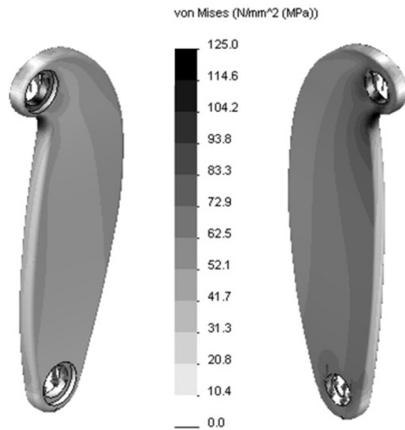


Fig. 17. Tension distribution in the front connecting rod

4 PROTOTYPE BUILDING AND TESTING

The next phase in the development of the prosthetic knee for alpine skiing was building a prototype and its testing in real-life conditions.

On the basis of the virtual model, two prosthetic knee prototypes, called *Art-Leg Sport Knee*, were built, as shown in Fig. 19.

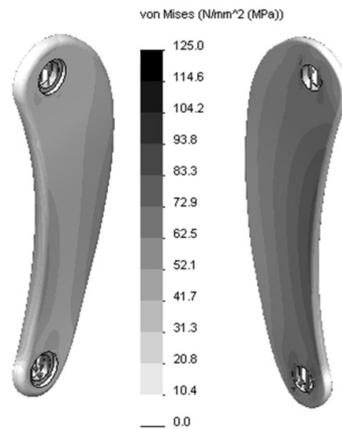


Fig. 18. Tension distribution in the rear connecting rod



Fig. 19. *Art-Leg Sport Knee* prosthetic knee prototype



Fig. 20. Above-knee prosthesis assembly for alpine skiing

The whole assembly of the above-knee prosthesis for alpine skiing is shown in Fig. 20. Together with the prosthetic knee, which is at the core of the prosthesis, existing, i.e. standard prosthetic elements, were used for building the prosthesis (socket, foot, adapters, fixing elements etc.).



Fig. 21. *Skiing with the above-knee prosthesis (Kitzsteinhorn, October 2010)*

The prosthesis was tested using different skiing techniques and speeds. In cooperation with alpine skiing instructors, we observed the prosthesis response, particularly that of the prosthetic knee, to the situations that arise. We also observed the quality of turning and ski control throughout the turn. The vital information on the suitability of the prosthesis, particularly the prosthetic knee, was provided by the skier (user) according to his feelings and advanced skiing skills.

6 RESULTS

The test results confirmed the suitability of the selected concept of the multi-axis mechanism that simultaneously provides knee flexion-extension and translation, which enables maintaining optimum position of the centre of gravity throughout the turn (Fig. 22).

The selected combination of a shock absorber and a spring coil, which together with mounting geometry provided variable resistance at different contracture angles, proved to be a good solution. In left turns, where the prosthesis was on the outer side, it provided suitable resistance and consequently load transfer to the outer ski, which reduced knee contracture. A little more effort and

adaptation was required for right turns, where the prosthesis is on the inner ski and more contracture in the knee joint is required. In this case, less resistance in the knee contracture phase would be required, which would also lead to smaller load on the inner ski and thus better ski control in right turns. The knee itself allows it (Fig. 16). However, the feeling is unusual when resistance at knee contracture from a certain angle onwards weakens, which takes some getting used to.

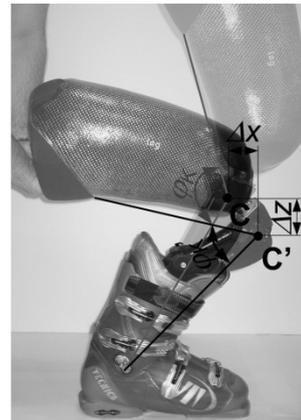


Fig. 22. *Above-knee prosthesis with prosthetic knee Art-Leg Sport Knee*

After two-day testing on a ski slope (cold, snow, real physical stress) we also checked visually and by means of geometry the suitability of the prosthetic knee structure from the viewpoint of wear and other defects (ventilation, deformation, etc.). There were no visible traces of use, which confirms strength appropriateness of the structure and the correctness of choice and accuracy of strength control.

7 CONCLUSION

Judging by the results of prosthesis (prosthetic knee) testing on a ski slope we conclude that with proper knowledge, a correct approach and carefully selected working methods it is possible to significantly improve patient care with special aids after leg amputation.

Although the prosthetic knee does not allow lateral knee flexing (abduction/adduction), which is not significant in skiing anyway, the prosthesis allows skiing with the carving technique, as well as turning with skidding, which

makes it suitable for the entire range of skiers. It is necessary to adjust the prosthetic knee according to the skier's psychophysical abilities and his or her skiing skills.

The prosthetic knee can also be used for other activities, such as snowboarding, wakeboarding, skateboarding, water skiing, surfing, skating, rollerblading, etc. Owing to its structure, it keeps the body in the optimum position during sports activity. When the user squats, its centre of gravity does not move backwards, but does exactly the opposite - prosthetic knee shrinks and moves forward, keeping the user in its optimal position.

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