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KNEE DYNAMIC ANALYSIS IN THE DEVELOPMENT OF ABOVE KNEE PROSTHESIS FOR ALPINE SKIING

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ABSTRACT

The development of biomechanical systems requires detailed knowledge of a natural system. The work includes an analysis of the natural process of the kinematics and dynamics in the knee joint in a laboratory simulation of motion through a ski turn. Measurements and analyses of the results are the foundation for the development of the prosthetic knee for ordinary two-track skiing for above the knee amputees. A dedicated testing facility was built, allowing simultaneous capturing of leg structure kinematics and surface loading rates. Changing additional vertical loads in the waist area, different conditions of performing a ski turn were simulated.

Measuring the kinematics and dynamics of a control group of able-bodied skiers show that rotation in the knee joint is below 60°. Longitudinal force in the knee reaches values of up to 1.2 N/kg. Average vertical load in the knee exceeds 10 N/kg. The knee flexing/extension moment reaches values of over 1.5 Nm/kg. The presented laboratory measurements are comparable with those on ski slopes and represent the basis for the development of tailor-made prosthetic knees.

Keywords: new product development, simulation, above-knee amputation, alpine skiing, kinematics, dynamics analysis.

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1 INTRODUCTION

Alpine skiing is a hugely popular winter sport. Besides ordinary skiers, a significant proportion belongs also to leg amputee skiers (McCormick, 1984, Natri, Beynnon et al., 1999, O'Leary, Meinig et al., 1989). Due to all sorts of accidents, the number of young people being re-integrated into active life has significantly increased (Burger, 2010). There is a number of aids – from simple ones at affordable prices to advanced and expensive ones (Burger, 2009) – to help perform the basic life functions, such as walking. Whenever this threshold is crossed, the choice becomes very limited or almost non-existent. Developing such accessories therefore creates many opportunities for the development of new products (Benedičič, 2012, Žavbi, 2010).

A majority of people with an above-knee amputation ski on an intact leg only with a use of so-called three-track skiing technique (Jessen, 2012, McCormick, 1984). This technique involves skiing on an intact leg only by using special poles (crutches) with skis fixed at the bottom (Figure 1a).Regular skiing on both legs (intact leg and prosthetic leg) (Figure 1b) is used very rarely in people with above-knee amputation (Demšar, Supej et al., 2011, McCormick, 1984).

Figure 1. Skiing with an above-knee amputation; a) three - track skiing – skiing on the sound leg with the assistance of two specially designed poles, b) regular skiing on both legs - intact leg and prosthetic leg.

Leg kinematics and dynamics in particular are substantially different in skiing, compared to walking. What is important in walking, is leg/prosthesis response in the swing phase and stabilization on landing (Jaegers, Arendzen et al., 1995, Powers, Rao et al., 1998), while in skiing the emphasis is on transferring loads via the leg/prosthesis onto the ski through the entire turning phase (Müller and Schwameder, 2003).

Developing a special prosthetic knee for the above knee prosthesis for alpine skiing first of all requires a good understanding of the natural process (Duhovnik, 2003, Engineers, 1993). To this purpose, a special testing facility was designed in order to record the natural process of motion and stresses in the knee joint while simulating the motion through a ski turn. Adequately analysing the kinematics and dynamics in the knee joint of an able-bodied skier, it is our objective to precisely define functional requirements for the development of a new prosthetic knee (Duhovnik, 2005).

The purpose of this paper is to present a method of defining design requirements for the development of a biomechanical prosthetic knee system for above the knee amputee alpine skiers for regular skiing on both legs – intact and prosthetic (Figure 1b). Measured and analysed were the kinematics and dynamics of the leg structure, particularly the knee joint, at laboratory simulation of the motion through an alpine skiing turn. Presented are the testing facility concept, the measurement system and processing the measurements.

2 METHODS

The development of biomechanical systems, including the prosthetic knee for alpine skiing, should be based on an analysis of a natural process (a bionic system). For this purpose, we expanded the design and development process according to VDI-R 2221 recommendations (Engineers, 1993) by analysing the natural process (Figure 2). By analysing the kinematics and dynamics in the knee joint of an able-bodied skier, it is our objective to set the values of the key parameters that provide the basis for the development of the prosthetic knee for above the knee amputee alpine skiers.

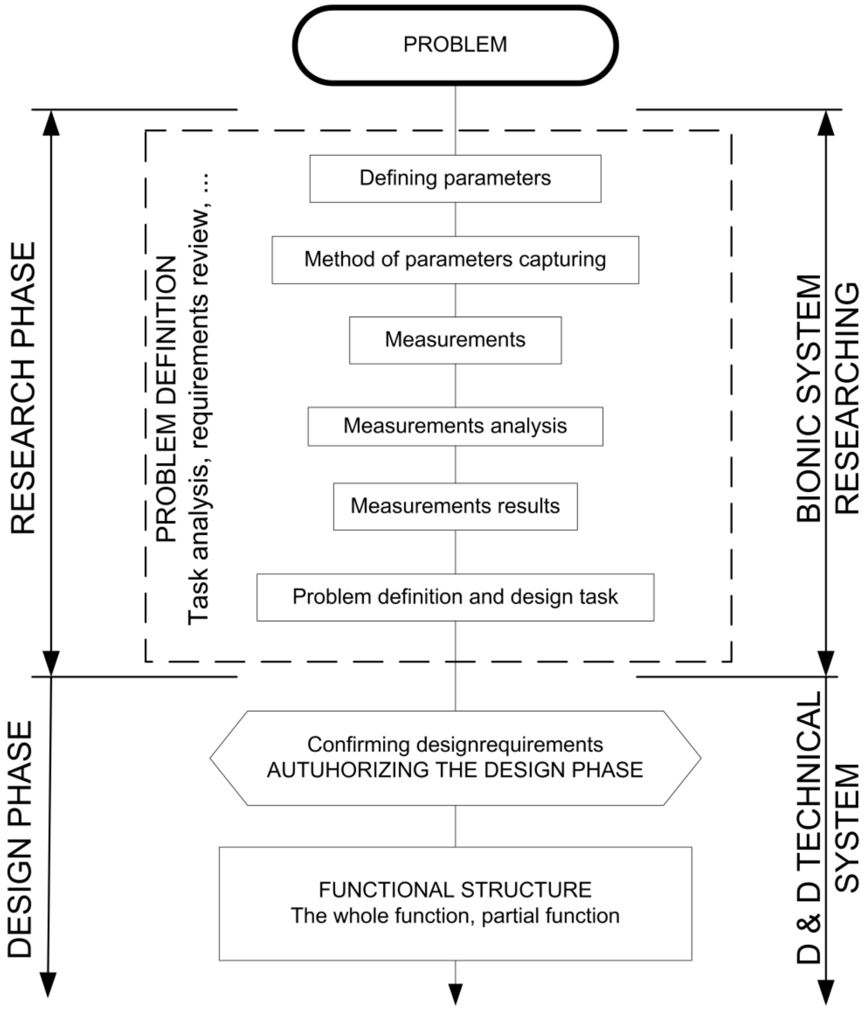


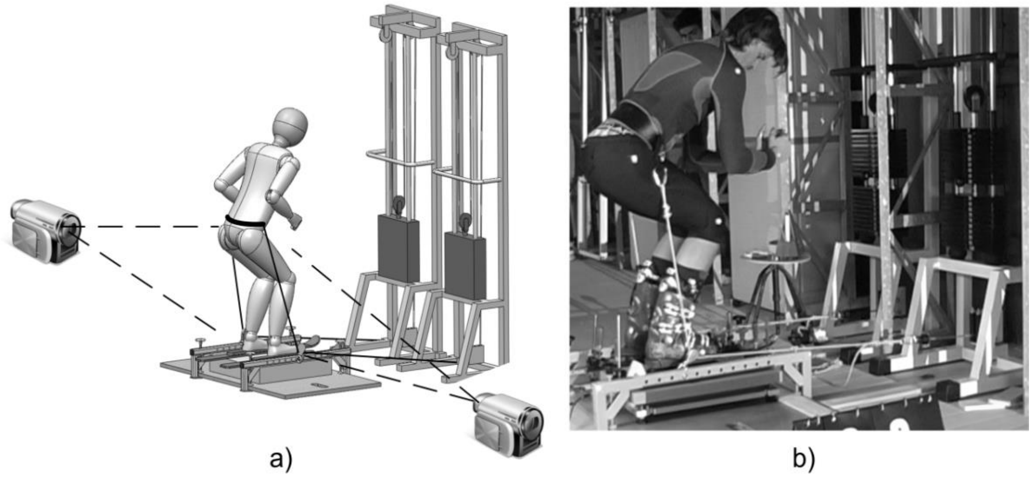
Figure 2. Analysing a bionic system in the product development phase

During the first phase it is initially necessary to define the design parameters that a technical system should fulfil. In the case of the prosthetic knee for alpine skiing it includes adequate kinematics, i.e. rotation of the prosthetic knee and corresponding dynamics (forces and moments). The next phase requires developing the method of data collection. This is followed by performing the measurements, their analysis and results. Only on this basis is it possible to create a design requirement, followed by the concept phase.

Experiment setup and data collection

Measuring the knee joint kinematics and dynamics took place in a laboratory, on a purpose-built testing facility (Figure 3), allowing simultaneous capturing of leg structure kinematics and surface reaction forces. A control group of eight measured individuals was selected. All of them are ski instructors and members of the demo team Slovenia. Kinematics measurements were captured on the right side. Reaction forces and moments were captured simultaneously for both legs.

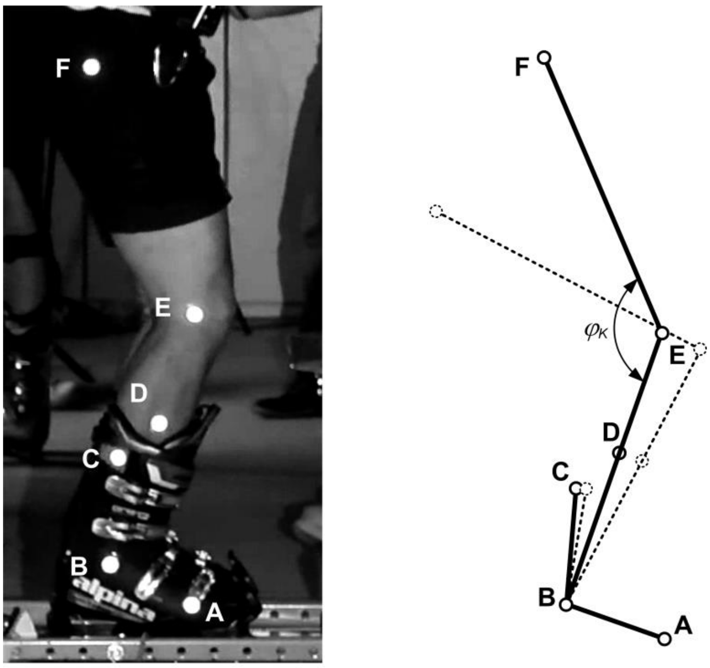
Four sets of measurements were recorded. The first set was captured without any additional loads. By increasing vertical load in the waist area we simulated additional pressure that the skier is subject to when making a turn. It means that the second, third and fourth set of measurements included additional loads of +1/3, +2/3 and +3/3 of skier's own weight, respectively. Each set of measurements included at least ten cycles of up and down movements. The measurements took place in an air-conditioned laboratory at a temperature of 18° C. Ski boots and the prosthetic assembly were pre-cooled to a temperature of approximately +5° C.



a) b)

Figure 3. Testing facility a) concept, b)measurement

Capturing leg structure kinematics was carried out by an optical system, based on capturing 2-D images of control points movement in space. The control points were chosen so that they allowed monitoring individual segments in three degrees of freedom (Figure 4).



a) b)

Figure 4. Object of observation: a) location of control points on a measured individual; b) kinematic model with measured positions of control points: A - foot, B - ankle, C – ski boot, D - shin, E - knee and F – hip. $\boldsymbol{\varphi_K}$ *– knee angle.*

Capturing the location of control points in the sagittal plane was carried out by two high-frequency cameras Casio Exilim EX-F1 (Casio Computer Co., LTD, Tokyo, Japan). Images were captured at a frequency of 60 frames per second in a 1920 x 1080 pixel resolution. The cameras were positioned in the frontal plane, to the left and to the right of the measured person.

Together with leg movement at skiing and the location of individual control points, the measurement system included also a system for measuring reaction forces and moments upon surface. For this purpose, a force platform (Advanced Mechanical Technology Inc, Watertown, USA) was used. It captures data on the forces and moments in different directions in real time. The sampling speed was

300 Hz. Synchronizing kinematic and kinetic measurements was done by means of an outside force impulse (collision).

Calculation

The coordinates of individual points in a specific time were calculated by means of Matlab 2007a software (Mathworks Inc., Natick, MA). The knee angle (φ_K) was calculated from the position of control points B and E (the shin) and control points E and F (the thigh bone) (Figure 4b):

$$\varphi_K = cos^{-1}\left(\frac{-((x_F-x_B)^2+(y_F-y_B)^2)+(x_E-x_F)^2+(y_E-y_F)^2+(x_E-x_B)^2+(y_E-y_B)^2}{2\cdot\sqrt[2]{(x_E-x_F)^2+(y_E-y_F)^2}\cdot\sqrt[2]{(x_E-x_B)^2+(y_E-y_B)^2}}\right). \quad (1)$$

Given the fact that the knee angle depends on the initial position of control points and that no direct comparison is possible between the sound leg and the prosthesis, we used angle difference, i.e. rotation, instead of the ordinary biomechanical angle. Knee rotation ($\Delta\varphi_K$) was calculated as the difference between the widest angle, reached at a single measurement, and the current angle:

$$\Delta\varphi_K = \varphi_{K,max} - \varphi_K \quad (2)$$

In order to specify reaction forces and moments in the knee joint, the inverse dynamics method was used. Knowing the kinematics of individual segments and using accurate measurements of anthropometric data and outside loadings, we determined – by means of dynamic balance – internal forces and moments in the knee joint:

$$\sum F_i = m \cdot a\ , \sum M_i = J \cdot \alpha \quad (3)$$

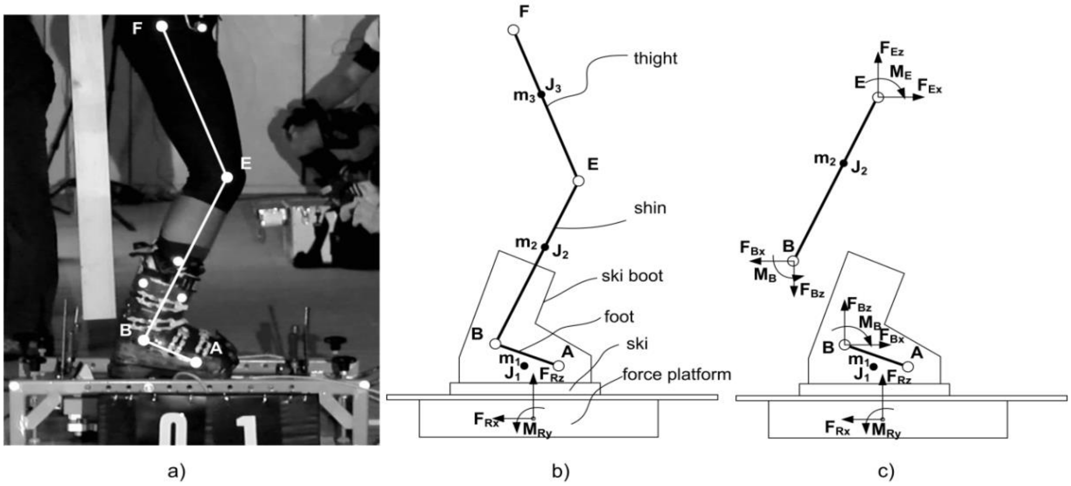


Figure 5: Model of the area of study; a) anatomic model, b) multi-segment model, c) itemised dynamic model

Segments characteristics (length, mass, the location of the centre of gravity and the radius of gyration) were measured directly on the measured person and read from corresponding anthropometric tables (Winter, 2009). With the above-knee prosthesis, i.e. the prosthetic knee, allowing 2-D kinematics only, we used dynamic balance in the sagittal plane (x-z) (Figure 5):

$$F_{Ex} = m_2 a_{2x} + F_{Bx} \quad (4)$$

$$F_{Ez} = m_2 a_{2z} + F_{g2} + F_{Bz} \quad (5)$$

$$M_{Ey} = J_2\alpha_2 - M_{SB} + M_B - F_{Ex} l_{T2}\, sin(\varphi_2) + F_{Ez} l_{T2}\, cos(\varphi_2) - F_{Bx}(l_2 - l_{T2})\, sin(\varphi_2) + F_{Bz}(l_2 - l_{T2})\, cos(\varphi_2) \quad (6)$$

Where:

m_1 … ski boot and foot mass,
m_2 … leg (shin) mass,
l_2 … leg (shin) length,
l_{T2} … distance between the leg's (shin's) centre of gravity and the knee joint,
a_2 … acceleration of the leg's (shin's) centre of gravity,
J_2 … leg's (shin's) moment of inertia,

α_2 … leg's (shin's) angular acceleration,
F_B, M_B … Reaction forces and moment in the ankle joint (point B),
F_E, M_E … Reaction forces and moment in the knee joint (point E).

3 RESULTS

Peak values of the knee rotation angle, knee forces in longitudinal and vertical directions, and moment in the knee joint for each measured person are given in Tables 1 and 2.

Table 1: Peak value of the knee rotation angle and knee force in longitudinal direction.

	Body Weight (BW) [kg]	Peak rotation of the knee joint [deg]				Peak knee force in the longitudinal direction F_{Ex} [N]			
		+ 0/3 BW	**+ 1/3 BW**	**+ 2/3 BW**	**+ 3/3 BW**	**+ 0/3 BW**	**+ 1/3 BW**	**+ 2/3 BW**	**+ 3/3 BW**
Subject 1	82.3	52.4	46.8	47.2	47.4	27.0	55.3	89.2	101.3
Subject 2	68.7	63.7	64.8	62.7	56.1	73.5	75.1	85.1	63.8
Subject 3	84.7	50.4	53.2	53.8	52.6	45.3	55.5	62.0	77.6
Subject 4	63.3	48.9	52.2	51.9	54.9	34.9	87.7	89.1	143.5
Subject 5	67.7	52.9	50.5	45.8	48.7	57.5	47.6	70.7	112.7
Subject 6	92.8	57.3	52.1	60.9	61.6	62.6	56.4	117.2	83.1
Subject 7	87.3	59.9	59.3	55.9	55.5	65.7	76.1	106.6	119.9
Subject 8	80.6	60.0	57.4	62.9	59.4	87.0	46.8	100.5	94.8

Table 2: Peak value of the knee force in vertical direction and knee flexion/extension moment.

	Body Weight (BW) [kg]	Peak knee force in the vertical direction F_{Ez} [N]				Peak knee flexion/extension moment M_{Ey} [Nm]			
		+ 0/3 BW	**+ 1/3 BW**	**+ 2/3 BW**	**+ 3/3 BW**	**+ 0/3 BW**	**+ 1/3 BW**	**+ 2/3 BW**	**+ 3/3 BW**
Subject 1	82.3	-578.0	-699.8	-859.9	-1039.3	-54.2	-96.4	-121.9	-140.4
Subject 2	68.7	-588.7	-684.3	-725.7	-814.3	-73.9	-96.7	-97.5	-123.4
Subject 3	84.7	-651.4	-884.8	-862.6	-1099.0	-44.6	-90.5	-100.8	-145.9
Subject 4	63.3	-448.7	-558.4	-639.8	-776.7	-53.5	-73.6	-98.4	-121.8
Subject 5	67.7	-646.2	-709.2	-840.8	-932.3	-44.7	-74.6	-94.0	-104.2
Subject 6	92.8	-777.9	-861.7	-1040.2	-1133.0	-63.8	-85.9	-137.3	-136.6
Subject 7	87.3	-757.5	-876.7	-991.7	-1195.5	-64.3	-85.3	-119.7	-133.8
Subject 8	80.6	-701.3	-863.9	-1065.1	-1147.9	-41.3	-46.6	-111.9	-139.6

Because forces and moments depend on the measured person's body mass, the results below are shown by mass units. Figure 6 shows mean values (± SD) of parameters by the proportion of the cycle. One cycle means one motion from the upper to the bottom position (flexion – extension).
When specifying design requirements and developing a technical system, more important than the value of parameters in terms of the proportion of the cycle are the values of forces and moments in the knee joint in terms of its rotation (Figure 7).

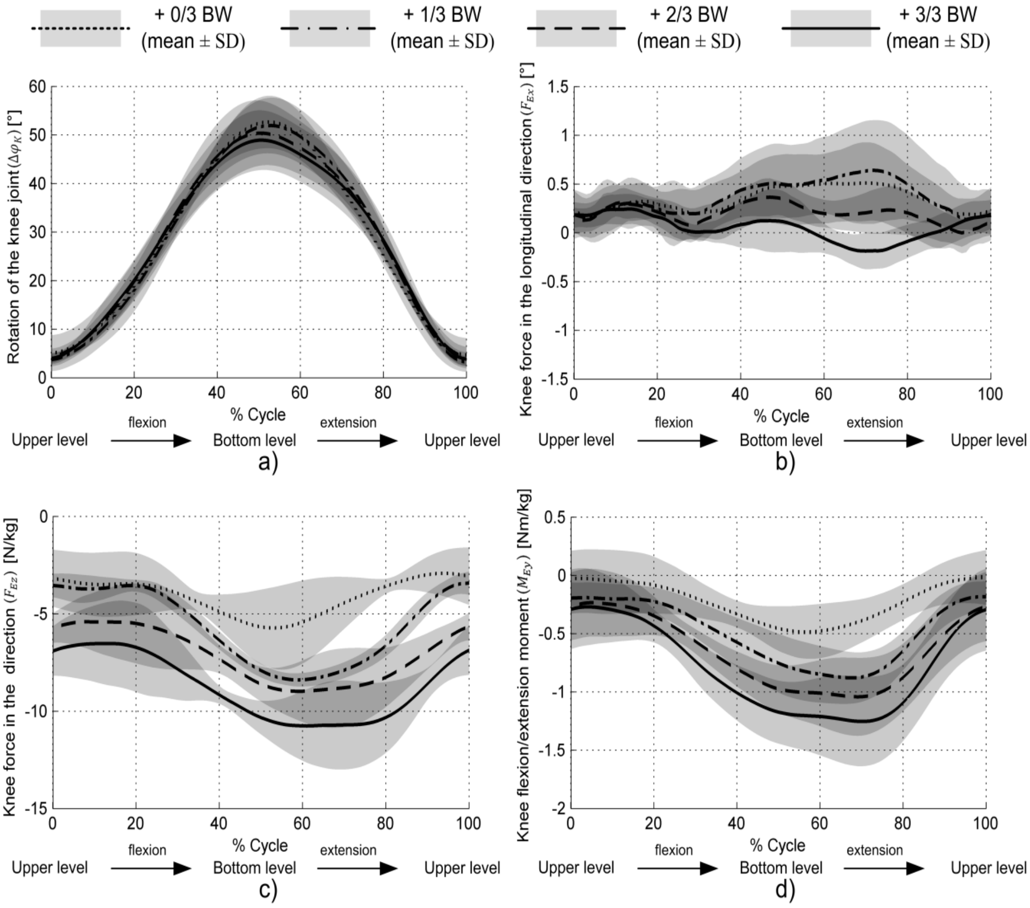


Figure 6. Mean value (± standard deviation) of parameters by the proportion of the cycle: a) rotation of the knee joint ($\Delta\varphi_K$), b) knee force in the longitudinal direction (F_{Ex}), c) knee force in the vertical direction (F_{Ez}), d) knee flexion/extension moment (M_{Ey}).

4 DISCUSSION

The study represents an approach to specifying design parameters for the development of a prosthetic knee for above the knee amputee alpine skiers. The key feature of the prosthetic knee is to provide suitable kinematics and dynamics that alpine skiing requires. For this purpose the kinematics and dynamics process of ordinary (able-bodied) skiers were analysed. Analysed were the angle (rotation) and forces and moments in the knee joint.

It has been found that the average knee joint rotation is around 50°. By adding vertical load it even decreases a little. The knee force in the longitudinal direction is between -0.5 and 1.2 N/kg. In the vertical direction, the knee force changes together with the amount of additional load and peak values can exceed 10 N/kg in the extension phase. The situation of the moment in the knee around the y-axis is similar. With an additional load of +3/3 BW it reaches the average value of up to 1.3 Nm/kg in the extension phase.

The key for the development of the prosthetic knee is the course of forces and moments relative to the rotation angle of the prosthetic knee (Figure 7). It shows that pressure is different (usually lower) in the flexion phase, compared to extension.

Considering the specific conditions, we simulated the execution of a ski turn in a purpose-built testing facility. Leg movements through ski turns were simulated by two-leg squats. The average frequency of up and down movements (cycle) was $1.1 \pm 0.3s$, which compares to a slalom turn (Supej, 2010). At measurements, additional loading, generated by skier's movement through a turn, was simulated by additional loads of between +1/3 BW and +3/3 BW, which is in accordance with previous researches (Yoneyama, Kagawa et al., 2000).

This study has several limitations that should be considered when interpreting the results. First, kinematics of an artificial limb allows only planar movements. As a result, kinematics and dynamics of legs were studied in sagittal plane only, although it is well known that for quality alpine skiing abduction/adduction and internal/external rotation are also needed (Yoneyama, Kagawa et al., 2000). Nevertheless, in squats there is also some degree of internal/external rotation (Böhm and Senner, 2008), therefore, a future study should observe how the limitation of internal/external rotation influences the movement of a skier with an above-knee amputation when using artificial limb with multiple-axes prosthetic knee.

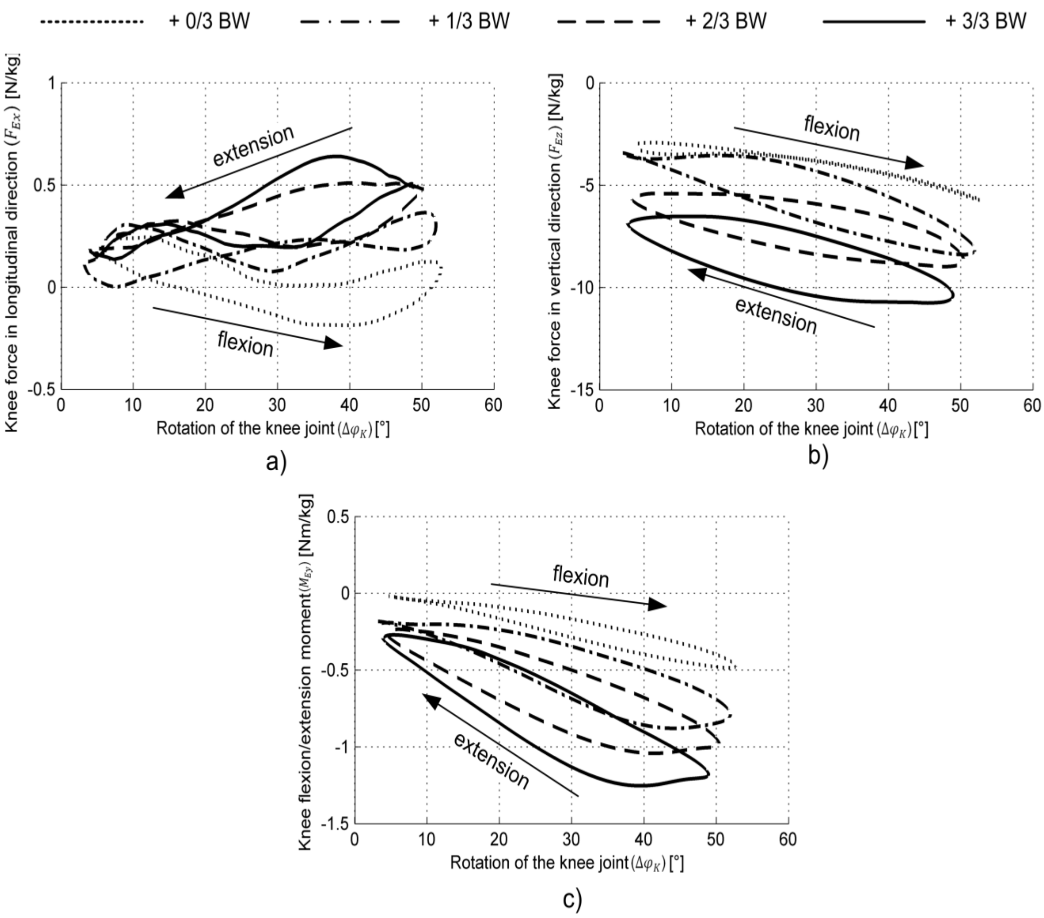


Figure 7. Mean value of knee rotation parameters ($\Delta\varphi_K$): a) knee force in the longitudinal direction (F_{Ex}), b) knee force in the vertical direction (F_{Ez}), d) knee flexion/extension moment (M_{Ey}).

Comparing knee kinematics and dynamics at a laboratory simulation of executing a turn and measurements on a ski slope confirms the suitability of the selected method. The peak mean value of knee rotation at an additional loading of +0/3BW ($50.1 \pm 5.6°$) compares to the values, measured on a ski slope (Supej, 2010, Yoneyama, Kagawa et al., 2000). Reaction forces and moment upon surface at an additional load of +3/3BW were also comparable with the reaction forces and moments, measured on a ski slope (Klous, Muller et al., 2012, Müller and Schwameder, 2003, Yoneyama, Kagawa et al., 2000).

We believe that an advantage of laboratory measurements over those on a ski slope is that they are easier to do and require no specific and expensive measurement equipment. In addition, they can be carried out in all seasons, and most of all, they, allow measuring above the knee amputees before prosthesis development actually begins. It will make it possible to adapt the prosthetic knee (prosthetic assembly) individually to a specific person.

5 CONCLUSION

The work represents a new approach to creating design requirements for the development of biomechanical systems. Presented is a concrete example of specifying knee kinematics and dynamics with laboratory simulation of alpine skiing. Measurement results show the comparability of measurements with those on a ski slope and thus the suitability of the selected method. In our opinion, the main advantage of laboratory measurements over those on a ski slope is that this method allows direct measuring of an above the knee amputee and direct adjustability to a concrete user.

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