The Biomechanics of Cycling with a Transtibial Prosthesis: A Case Study of a Professional Cyclist

D. Koutny, D. Palousek, P. Stoklasek, J. Rosicky, L. Tepla, M. Prochazkova, Z. Svoboda, P. Krejci

***Abstract*—**The article deals with biomechanics of cyclist with unilateral transtibial amputation. Transtibial amputation completely removes ankle and part of muscles of a lower leg which are responsible for production of force during pedaling and causes significant geometric and power asymmetry between the limbs during cycling movement. The primary goal of this work is to assess the effects of length adjustment of the crank on the kinematics and muscle activity of cyclist. The paper presents experimental work, which aims to find a suitable ratio of the length of kinematic components to improve overall athletic performance. The study presents the results of the kinematic analysis of the cycling movement with different crank length realized by tracking camera system together with the results of muscle activity measurements captured by electromyography and measurement of forces in the cranks by strain gauges.

***Keywords*—**Amputation, electromyography, kinematics of cycling, leg asymmetry, motion capture, transtibial prosthesis.

I. INTRODUCTION

ALTHOUGH modern cycling leg prosthesis intended for top sport are manufactured with advanced technologies from lightweight and durable materials, geometric deviations arise between prosthetic and healthy limbs during their use while pedaling. These deviations are characterized by angular rotation in the hip and knee. For proper bicycle ride and optimal (balanced) output of muscular energy, it is needed to reduce or completely suppress these deviations. This can be achieved by length modification of the components of the kinematic chain, which consists of a residual limb, prosthesis and pedal crank [1], [2].

Although cycling for people with amputations is considered as very beneficial health sport, it can have, particularly in performance at top level, a number of negative effects on the musculoskeletal system of the organism caused by unilateral loading. During cycling, there is no direct contact with the legs and ground and therefore there is no subsequent overloading of joints due to body weight or impact loading of musculoskeletal system as in other sports, however top cycling is associated with the emergence of various injuries and musculoskeletal problems [3], [4]. Appropriate crank arm length compensation under prosthetic limb would partially reduce uneven loading of muscles of whole body and thus have a positive effect on the body and health of racing cyclist.

Childers et al. [1], [2], [5] investigated the influence of various external factors on bicycling for individuals with unilateral transtibial amputation (bicycle positioning, crank shortening, stiffness of the prosthesis). Their work shows, that the shortening of the crank under prosthetic limb reduces force and geometric deviations between the legs, positively affects stereotype of pedaling and may contribute to a decrease in muscle loading of amputated limb. The authors also point to the fact that for the performance cycling in terms of transmission of higher driving forces is better to design and produce rigid prosthesis without flexible members simulating the ankle joint.

Moderate geometric and power asymmetry between the legs during cyclical movement is apparent also at healthy athletes. Carpes et al. [6], investigated asymmetry of the limbs during running and cycling. He pointed out a few interesting facts – asymmetry during pedaling of healthy athletes is probably connected with the limb dominance and is significantly reduced by increase of the load while pedaling (e.g. suitable change of gear ratio). In the research, Carpes also mentions that the elimination of the power imbalances between limbs is one of the most important factors for optimization of athletic performance, because it plays a significant role in the uniform production of driving torque. The phenomenon of force asymmetry of healthy cyclists during pedaling is probably caused by neuromuscular changes in the limbs after suffered injuries and is directly related to the influence of the limb dominance.

The influence of speed changes during pedaling on the motion asymmetry of lower limbs of healthy cyclists was done in other studies [7], [8]. The authors also concluded that the increase of the load while pedaling (by change of gear ratios) leads to reduction of the power and geometrical deviations between the legs.

There is large number of parameters that can be set and changed on the bike. Almost every element on the bike may be set incorrectly; which can result in improper involvement of the muscles during the pedaling cycle and therefore inefficient use of muscle potential. Appropriate setting of the bike (especially to the optimum saddle height) was studied by Burkett and Mellifont [9]. Their study describes the collaboration with the six-member Australian Paralympic

D. Koutny, D. Palousek, P. Stoklasek, and P. Krejci are with the Brno University of Technology, Faculty of Mechanical Engineering, Institute of Machine and Industrial Design, Technicka 2, 616 69 Brno, Czech Republic (e-mail: koutny@fme.vutbr.cz; palousek@fme.vutbr.cz, p.100klasek@gmail.com, krejci@fme.vutbr.cz).

J. Rosicky is with the University of Ostrava, Faculty of Health Studies, Department of Rehabilitation, Syllabova 19, 703 00 Ostrava 3, Czech Republic (e-mail: jiri.rosicky@osu.cz).

Z. Svoboda, M. Prochazkova, and L. Tepla are with the Palacký University, Faculty of Physical Culture, Department of Natural Sciences in Kinanthropology, Křížkovského 8, 771 47 Olomouc, Czech Republic (e-mail: zdenek.svoboda@upol.cz, marketa.prochazkova@upol.cz, lucie.tepla01@upol.cz).

cycling team during preparation for the Paralympic games. Half of the team reduced the seat height in the range of 10-19mm, the second half increased the saddle height in the range of 3-12mm. These changes have had an impact on the range of motion (ROM) in the hip joint, but did not show any change in the performance of cyclists when driving in the same conditions. This relatively simple resetting reduced the height of the rider in the frontal plane, which may cause in longer races achievement of better performance (higher speed), especially in terms of improvement of the overall aerodynamics of the rider. The authors mention that the integration of sports science combined with expert guidance and appropriate training program can have a positive impact on the overall performance of sports cyclists with amputation, their safety and health.

II. Methods

Further described experiments involved a male performance cyclist, 37 years old, 70kg, 188cm, with handicap: C4 - unilateral below-knee amputation of the right leg. Cyclist uses custom-made transtibial cycling prosthesis and carbon-fiber socket without mechanical members supplemented with duralumin adapter with a cleat to fasten directly to the pedal surface. The prosthesis is attached to the stumb by vacuum clamping system on a silicone liner Iceross Seal-In X5 (Össur, Reykjavik, Iceland).

Fig. 1 Prosthesis structure

The aim of the experimental part of this case study was to investigate the effects of length adjustment of the crank on the kinematics and muscle activity of cyclist. A motion capture system and measurement of muscle activity in the legs were used during riding in the seated position and in the climbing position. Both measurements were performed synchronously under the supervision of trained personnel under the same riding conditions. To ride in the seated position a riding parameters of 140 W and 70 rpm were chosen and for a ride in the climbing position 160 W and 80 rpm were used. These parameters were monitored on the rear bicycle wheel with a wireless performance and speed sensor by cyclo-computer Cycle Ops Power (Cycle Ops, Madison, USA). Rear wheel of the racing bike was clamped in a magnetic trainer. The six30 seconds measurements were performed for three different settings of bicycle crank length (three in seated and three in climbing position). The bicycle crank length of 175mm (original crank length), 167.5mm and 160mm were used.

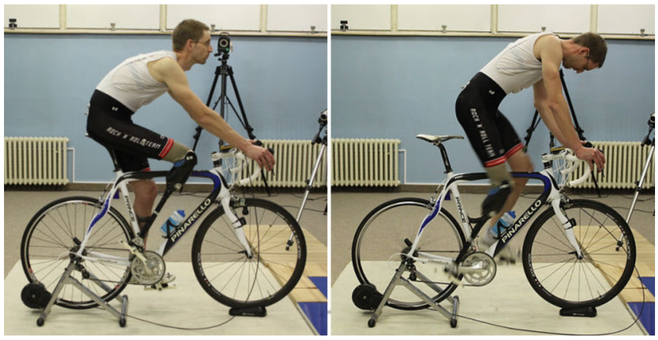

Fig. 2 Seated position (left) and climbing position (right)

A. Kinematic Analysis

For all measurements of kinematics was used a six-camera Vicon MX system (Vicon Motion Systems, Oxford, UK) with a frequency of 200Hz scanning. For evaluation of the kinematic parameters program Vicon Nexus 1.0 (Vicon Motion Systems, Oxford, UK) with a Plug In Gait model was used. On the lower limbs and pelvis of the cyclist a 14 reflective markers were placed (8 on the healthy limb 6 on side of prosthetic limb). On the side of prosthetic limb there was not necessary to trace the movement of the heel and toe.

Fig. 3 Reflective markers on health limb (left), on prosthesis (right)

The values of angular rotation in selected joints were evaluated in 5 consecutive cycles (5x turning a right crank about the 360°). On the basis of these results a percentage difference between the angular rotation in the hip and knee of prosthetic limb in comparison of the healthy limb were expressed.

For both lower limbs were observed values of the angular rotation of the hip joint (the angle between the femur and vertical line) and knee joint (for the healthy limb: the angle between the femur and tibia, for the prosthetic leg: the angle between the femur and prosthetic pylon).

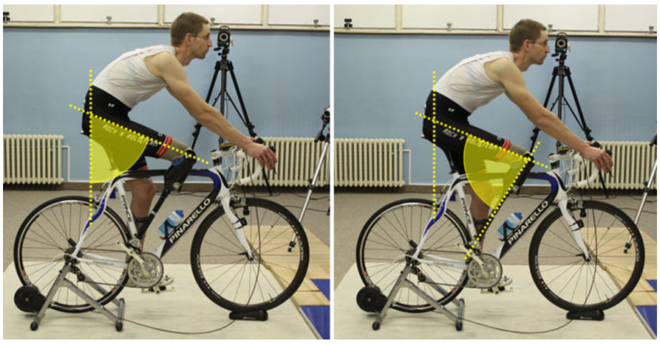

Fig. 4 Graphical representation of measured angles

B. EMG Measurements

For all measurements of muscle activity an EMG sensors Trigno Wireless Systems (Delsys, Boston, USA) were used. Surface electrodes (TrignoTM Wireless) were applied on the midpoint of the contracted muscles belly, parallel to the muscle fibers on the following muscles: the biceps femoris, semitendinosus, gluteus maximus, quadriceps femoris – part m. vastus medialis and m. vastus lateralis. The skin was shaved and cleaned with and ECG&EEG abrasive skin prepping gel (NuprepTM) to reduced skin impedance. All electrodes were fixed on the skin with adhesive tapes.

For evaluation of the EMG signal an EMG works program (Delsys, Boston, USA) was used. The raw EMG signals were amplified (gain = 2500), band pass filtered (20 - 450 Hz), an analog-to-digital converted at a sampling rate frequency of 4000/296 Hz. The EMG signal was also full-wave rectified and smoothed (Butterworth filter, second-order, cut-off frequency of 12 Hz). Finally root mean square procedure (window length 0.125; windows overlap 0.0625) was applied. EMG activity between the muscle activity in amputated limb in comparison of the healthy limb recorded during the test situation was expressed relative to the threshold muscle activity. The threshold muscle activity was calculated as average + two standard deviations of muscle activity recorded in resting cycling position. The activity level of each muscle was calculated for five consecutive crank cycles and normalized to the threshold value of each muscle.

C. Strain Gauge Measurements

For comparison of the influence of the crank shortening on the actual produced force during pedaling a separate measurement of the forces in the bicycle cranks was done. The measurement of the dominant bending strain in the crank arm was done by strain gauges connected in full-bridge arrangement compensating tension and torsion. Placement of strain gauges was determined on the basis on finite element analysis of the crank. For signal transmission from the strain gaugesan onsite developed wireless system was used (Fig. 5).

Signal and data processing were done in Matlab software.

Fig. 5 Wireless strain gauge measurement of cranksforces

III. Results

A. Kinematic Analysis

The results of kinematic measurement for riding in the seated position are shown in Tables I-III, the results of kinematic measurement for riding in the in the climbing position are shown in Tables IV to VI.

TABLE I
Hip and Knee Angles - Crank Length 175mm, Seated Position

CONDITION	**HIP ANGLE** [°]			**KNEE ANGLE** [°]		
	MIN	MAX	ROM	MIN	MAX	ROM
health limb	43	82	**39**	42	116	**74**
amputated limb	40	86	**46**	23	99	**76**

TABLE II
Hip and Knee Angles - Crank Length 167.5mm, Seated Position

CONDITION	**HIP ANGLE** [°]			**KNEE ANGLE** [°]		
	MIN	MAX	ROM	MIN	MAX	ROM
health limb	45	83	**38**	40	114	**74**
amputated limb	39	84	**46**	24	98	**74**

TABLE III
Hip and Knee Angles - Crank Length 160 mm, Seated Position

CONDITION	**HIP ANGLE** [°]			**KNEE ANGLE** [°]		
	MIN	MAX	ROM	MIN	MAX	ROM
health limb	44	83	**39**	38	117	**79**
amputated limb	44	85	**40**	28	97	**69**

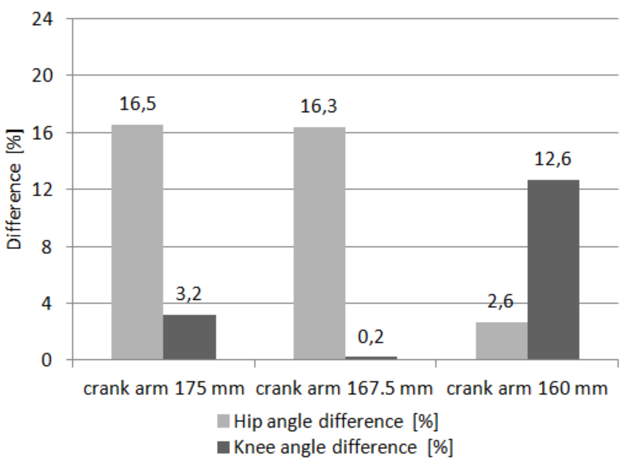

Fig. 6 ROM geometric asymmetries – seated position

TABLE IV
HIP AND KNEE ANGLES - CRANK LENGTH 175 MM, CLIMBING POSITION

CONDITION	HIP ANGLE [°]			KNEE ANGLE [°]		
	MIN	MAX	ROM	MIN	MAX	ROM
health limb	29	71	**41**	35	115	**79**
amputated limb	20	73	**52**	9	94	**85**

TABLE V
HIP AND KNEE ANGLES - CRANK LENGTH 167.5MM, CLIMBING POSITION

CONDITION	HIP ANGLE [°]			KNEE ANGLE [°]		
	MIN	MAX	ROM	MIN	MAX	ROM
health limb	30	73	**43**	27	114	**88**
amputated limb	24	74	**50**	10	93	**83**

TABLE VI
HIP AND KNEE ANGLES - CRANK LENGTH 160 MM, CLIMBING POSITION

CONDITION	HIP ANGLE [°]			KNEE ANGLE [°]		
	MIN	MAX	ROM	MIN	MAX	ROM
health limb	28	70	**42**	23	111	**88**
amputated limb	23	73	**50**	8	91	**83**

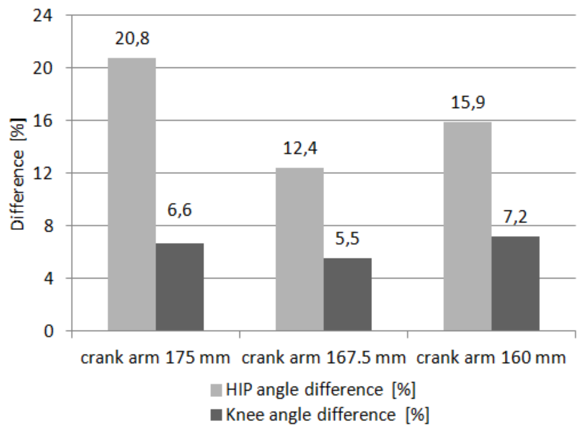

Fig. 7 ROM geometric asymmetries – climbing position

B. EMG Measurements

The evaluation of the measurement results of muscle activity is based on the threshold values of individual muscles recorded in the resting cyclist position.

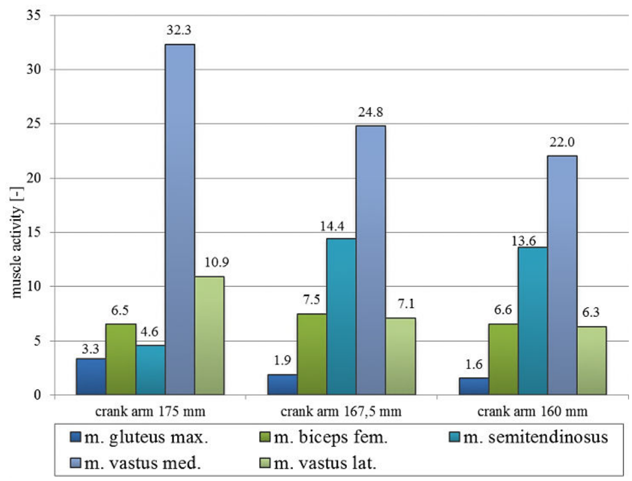

Fig. 8 Muscle activity in amputated limb – seated position

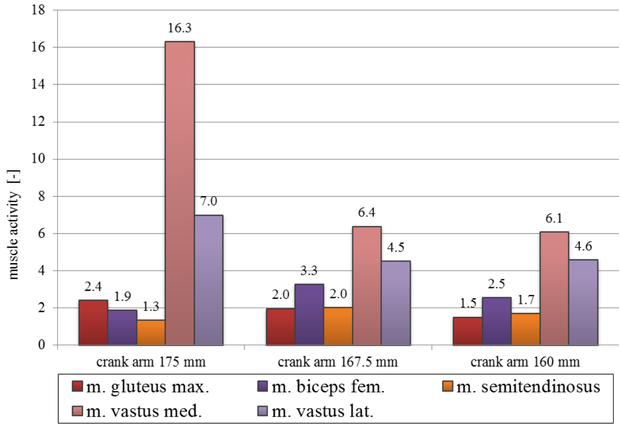

Fig. 9 Muscle activity in health limb – seated position

The evaluation of muscle activity of individual muscles for the seated position showed the following findings:

- Muscle activity of amputated limb is much higher than the healthy limb muscle activity.
- Any change in muscle activity in the muscles of amputated limb also affects the muscle activity of healthy limb.
- Due to the shortened length of the crank arm, while riding in the seated position, there is a decrease in muscle activity of the quadriceps femoris and gluteus maximusat both limbs.
- Due to the shortened length of the crank, while riding in the seated position, there is an increase in muscle activity of biceps fem. and semitendinosus in both limbs (Figs. 8 and 9).
- In terms of balanced muscular activity for the ride in the seated position, shortening of the crank to 160 mm appears to be optimal.

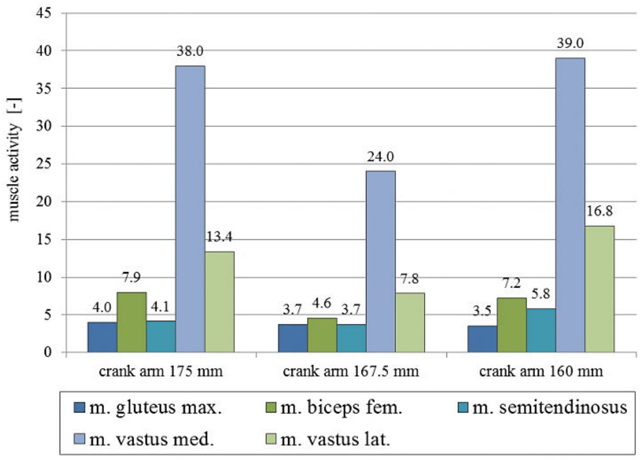

Fig. 10 Muscle activity in amputed limb – climbing position

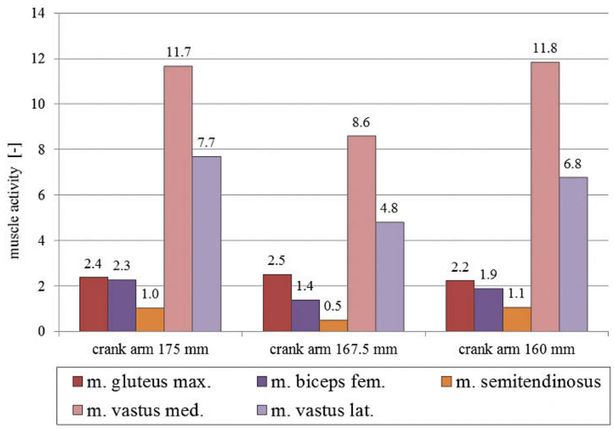

Fig. 11 Muscle activity in health limb – climbing position

The evaluation of muscle activity of individual muscles for the climbing position showed the following findings:

- Muscle activity of amputated limb is much higher than the muscle activity of healthy limb.
- When shortening the length of the crank to 160mm for riding in climbing position muscle activity of the amputated limb in the gluteus max. decreases, while activity of other observed muscles increase.
- In terms of balanced muscular activity for the ride in climbing position, shortening of the crank to 167.5mm appears to be optimal.

C. Strain Gauge Measurements

The forces produced by health and prosthetic limbs during the pedaling shows expected significant difference between the limbs. The force produced by prosthetic limb is about 42% lower than the health limb. As can be seen on the Figs. 12 and 13, the values of forces are not influenced by the change of crank length. However, the measurement was done independently on the EMG; therefore, further verification by complex measurement needs to be done.

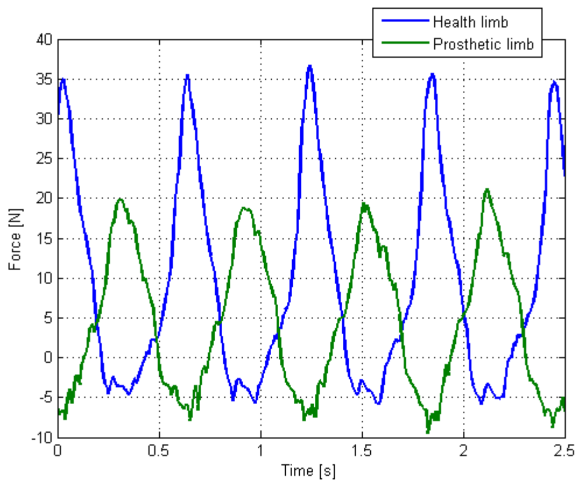

Fig. 12 Forces in the cranks – seated position, 167.5mm

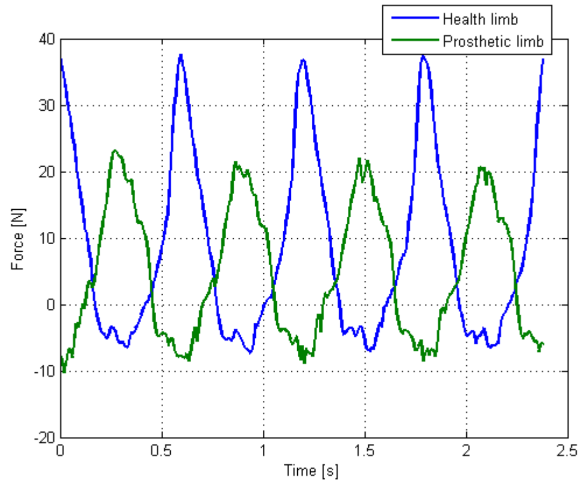

Fig. 13 Forces in the cranks – seated position, 175mm

IV. Conclusion

This article shows the influence of the crank length adjustments on the geometric deviations between the movement of prosthetic and healthy limbs during cycling of the handicapped performance cyclist.

Based on the results of kinematic analysis, EMG measurement and evaluation of subjective perceptions of the participating cyclist, the most suitable variant was the crank with the length of 167.5 mm.

Shortening of the bike's crank at the prosthetic limb can bring more symmetrical involvement of the limbs during the pedaling and therefore possible improvement of athletic performance of the cyclist with transtibial prosthesis. Shortening of the bike's crankat the prosthetic limb also has a positive effect on the activity of the muscles of the lower limbs during pedaling. Due to the shortening of crank length, activity of most of the monitored muscles decreased in comparison with the original state. However, the forces on the cranks did not significantly change with crank shortening. This can lead to lower muscle exhaustion and to overall better performance during the long races.

Acknowledgment

The work was supported by European Regional Development Fund in the framework of the research project NETME Centre under the Operational Programme Research and Development for Innovation. Registered no: CZ.1.05/2.1.00/01.0002, ID code: ED0002/01/01, project name: NETME Centre –New Technologies for Mechanical Engineering and project of specific research FSI-S-11-30/1454. The authors acknowledge the patience of the subject that participated in this case study and the MCAE Systems, s.r.o. for modification of the cranks.

All authors report no conflicts of interest.

References

[1] Childers, W. L.; Kistenberg, R. S.; Gregor, R. J. The biomechanics of cycling with a transtibial amputation: Recommendations for prosthetic

design and direction for future research. Prosthetics and orthotics international, 2009, 33.3: 256-271.
[2] Childers, W. L. Motor control in person with trans-tibial amputation during cycling. 2011. Dissertation. Georgia Institute of Technology, School of Applied Physiology.
[3] Schwellnus, M.; Derman, E. Common injuries in cycling: Prevention, diagnosis and management. SA Fam Pract. 2005, 47, 7, p. 14-19.
[4] Clarsen, B; Krosshaug, T; BAHR, R. Overuse injuries in professional road cyclists. The American journal of sports medicine, 2010, 38.12: 2494-2501.
[5] Childers, W. L.; Gregor, R. J. Effectiveness of force production in persons with unilateral transtibial amputation during cycling. Prosthetics and orthotics international, 2011, 35.4: 373-378.
[6] Carpes, F. P.; Mota, C. B.; Faria, I. E. On the bilateral asymmetry during running and cycling–A review considering leg preference. Physical Therapy in Sport, 2010, 11.4: 136-142.
[7] Smak, W.; Neptune, R. R.; Hull, M. L. The influence of pedaling rate on bilateral asymmetry in cycling. Journal of biomechanics, 1999, 32.899: 906.
[8] Sanderson, D. J. The influence of cadence and power output on the biomechanics of force application during steady-rate cycling in competitive and recreational cyclists. Journal of sports sciences, 1991, 9.2: 191-203.
[9] Burkett, B.; Mellifont, R. Sport science and coaching in Paralympic cycling. International Journal of Sports Science and Coaching, 2008, 3.1: 95-103.