Bio-Medical Materials and Engineering 26 (2015) S381–S388
DOI 10.3233/BME-151326
IOS Press

Reduced knee hyperextension after wearing a robotic knee orthosis during gait training - a case study

Yurong Mao[a,b], Wai Leung Lo[a,b], Guangqing Xu[a,b], Leonard Sheungwai Li[c], Le Li[a,b,*] and Dongfeng Huang[a,b,*]

[a] *Department of Rehabilitation Medicine, The First Affiliated Hospital, Sun Yat-Sen University, Guangzhou, 510080, China*

[b] *Guangdong Provincial Research Center for Rehabilitation Medicine and Translational Technology, Guangzhou, 510080, China*

[c] *Division of Rehabilitation Medicine, University Department of Medicine, Tung Wah Hospital, Hong Kong*

Abstract. This case study describes the effects of a wearable dynamic knee orthosis to supplement walking training in a patient suffering knee hyperextension. The subject was a 57-year old female who was 3.5 years post-brain tumor surgery. She was presented with impaired right lower extremity muscle performance, increased lower extremity muscle tension, and right knee hyperextension. She reported pain at the right knee joint and tibialis anterior after 10 minutes of over-ground walk. Fifteen one-hour sessions of gait training with robotic knee orthosis (RKO) were provided an over 3 weeks period. The subject demonstrated improvement with right lower limb kinematic and kinetic measures of gait. Peak flexion degree and moment increased (from -4.99° to 13.47°, and from 0.18 Nm/kg to 0.20 Nm/kg respectively).Extension peak moment decreased from 1.03 Nm/kg to 0.53 Nm/kg. Knee joint force decreased from 0.68 N to 0.45 N. Ground reaction force (GRF) reduced from 11.06N to 10.11N. Berg Balance Scale (BBS) improved from 45/56 to 51/56. No difference was observed in Fugl-Meyer Assessment of the Lower limb (FMA-LE) scores. Gait training that integrates an intention-based RKO for correcting knee hyperextension can be clinically effective. The persistence and generalizability of these results need to be further investigated.

Keywords: Rehabilitation robot, gait analysis, knee hyperextension, robotic knee orthosis

1. Introduction

Human gait is based on optimality principles between fatigue-like and energy-related cost functions [1]. The joint locking mechanism between the femur and tibia could decrease muscle energy

* Address for correspondence: Le Li, Department of Rehabilitation Medicine, The First Affiliated Hospital, Sun Yat-Sen University, Guangzhou, 510080, China. Tel.: +86-20-87332200-8536; Fax: +86-20-87750632; E-mail: lile5@mail.sysu.edu.cn.
Dongfeng Huang, Department of Rehabilitation Medicine, The First Affiliated Hospital, Sun Yat-Sen University, Guangzhou, 510080, China. Tel.: +86-20-87332200-8532; Fax: +86-20-87750632; E-mail: huangdf@mail.sysu.edu.cn.

consumption. However, the straight-legged stance phase is hardly seen in normal walking and may contribute to muscle fatigue and pain. The normal range of motion for human knee flexion during walking and stair climbing is between 0 to 66 degrees [2]. Knee joint flexion is about 5 to 10 degrees during the stance phase and 40 to 60 degrees during swing phase [3]. For the knee joint to function efficiently during gait, coordinated co-contraction of the hamstring muscles and quadriceps femoris are required. Individuals with weak quadriceps, hamstrings or un-coordinated co-contraction contribute to knee hyperextension or genu recurvatum [4]. Literature has shown that decreased hamstring strength relative to quadriceps is a contributing factor to potential knee injuries [5].

Damage to the central nervous system (regardless of the cause) can result in knee hyperextension of paretic lower extremities. Genu recurvatum has been reported in approximately one half of hemiplegic patients and various rehabilitation techniques and orthotic devices have been shown to improve knee joint muscle strength and coordinated co-contraction during walking [6, 7]. Isometric, isotonic, and isokinetic exercise can increase muscle strength around the knee [8]. However, these exercises are not functions orientated and the benefits may not be carried over to activities of daily living. Functional strengthening exercises, such as sit to stand (STS), can simultaneously improve strength in quadriceps and hamstring muscles [9]. However, it is difficult for people with muscle weakness or dystonia to control the co-contraction required to perform an unassisted STS. Ankle-foot-orthoses (AFO) also has been reported to reduce knee hyperextension during the stance phase in children with cerebral palsy [10], but may not be effective in patients with severe knee genu recurvatum caused by weakness or spasticity of the knee muscles [4]. Additionally, AFO do not interfere with knee flexion during the swing phase [11]. A new wearable robotic knee orthosis (RKO) has been designed for mobility training with dynamic assistive and resistive knee joint forces, along with sensory inputs during walking or stepping on stairs. This orthosis has been used for gait training in hemiparesis after stroke and results demonstrated improvement in gait capability [12, 13]. The benefitting mechanism with RKO may be related to task-oriented training, such as climbing stairs, which requires increased balance and locomotion ability [12, 13]. Literature also suggested that the RKO could be used as a mechanized-knee extension assisting system to provide functional movement. This would lead to improve balance, gait and functional performance in hemiparetic patients [12, 13]. RKO may be beneficial in patients with knee hyperextension post brain surgery. It may re-educate normal knee joint movement and promote normal gait pattern. To date, the value of knee joint movement on motor recovery from genu recurvatum has not been demonstrated. 3D biomechanical analysis of knee joint movement and angle has not been conducted with RKO training. The purpose of this case study is to investigate the potential impact of wearable RKOs on knee hyperextension using 3D gait analysis of kinematic and kinetic parameters.

2. Method

2.1. Subject

Informed consent was obtained from the subject. A 57-year-old female complained of difficulty in walking and was accompanied with pain. She had previously undergone brain tumor surgery 3.5 years prior. She received medical treatment and traditional Chinese medicine after surgery. She had not received prior rehabilitation or physical therapy. She recovered well from the surgery but had residual neurological impairment that led to right lower limb weakness. She walked with hemiplegic and circumductive gait. One month before her first visit, brain MRI revealed local cysts in the operative area. She exhibited right-sided mild hypoesthesia and hypotonia, with decreased knee and ankle reflexes of the right lower extremity. Manual Muscle Test (MMT) demonstrated right quadriceps femoris and hamstring muscles to be grade 4 and grade 2. Iliopsoas and gluteus maximus were grade 3 and grade 2 respectively. Tibialis anterior and gastrocnemius muscles were both grade 4. Passive range of motion (PROM) with hip joint extension limited to 0^{0}. PROM of all other joints at the right lower limb was normal. A shortened stride length with knee hyperextension was exhibited while the patient walked on the level ground without the use of any aids or other orthoses. Step cadence was slightly faster (105 steps/min) when compare to normal. After walking for 10 minutes, the subject reported pain in the knee joint and tibialis anterior.

2.2. Justification for chosen subject

The patient was identified as a suitable candidate for using RKO for several reasons. She could not control the movement of her right knee during walking. Loss of flexion in the right knee was observed for the whole gait cycle. She demonstrated sufficient motor and balance abilities to wear the RKO system. She was able to perform 60 minutes of gait training. In addition, she complained that knee pain may cause over-pressure at the joint.

2.3. Equipment

A portable, wearable, battery-powered RKO (Tibion Bionic Leg, Tibion Corporation, Sunnyvale, CA, USA) was used. It acted like an orthopedic knee brace to provide support to the patient during walking over-ground and stepping on stairs (Figure 1C). The device has internal sensors at the foot and knee joints to detect intention of movement. Once a variable force threshold is reached, it provides the assistive and resistive force through the motor installed at the knee joint. A sound is also created to act as a feedback mechanism.

Kinematic parameters were measured using a Vicon system (VICON MX13, Oxford, UK) with six cameras (frame rate = 100 Hz).The captured data were subsequently analyzed using Vicon Nexus (Version 1.7.1) (Figure 1A). Kinetic data were collected simultaneously by two force plates (AMTI, Watertown, MA, USA) (Figure 1B) with sampling frequency of 1000 Hz.

2.4. Gait training

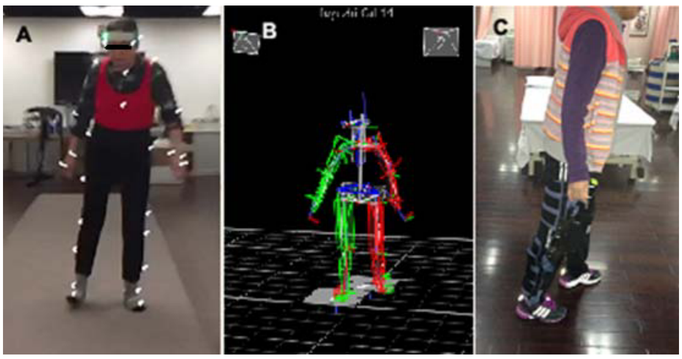

Fig. 1. Gait parameter capture and training. A- Three-dimensional kinematic data were recorded with cameras, and kinetic data were recorded by force plates under the carpet during walking. B - 3D perspective during gait analysis, with camera and force plate labeling. C- Demonstration of over-ground walking training using the RKO.

Table 1

Physical therapy training plan and RKO parameters

Week	Weight (kg)	Assist factor (%)	Resist factor (%)	Threshold (WT%)	Assisted extension limit (degrees)
Week 1	50	60	Middle	30	-5
Week 2	50	65	High	35	-10
Week 3	50	65	High	40	-15

The RKO-assisted gait training program included 15 sessions, conducted five times per week for 3 weeks (Table 1). Each session lasted for 60 minutes and consisted of 45 minutes level surface walking, and 15 minutes up/down stairs training. RKO was worn for the duration of the session. Five-minute breaks were taken whenever needed. One experienced physical therapist conducted all training sessions and supervised subject safety. Knee motion was observed all the time during her walking. She reported no pain when walking after the first week of training.

2.5. Data recording

Kinematic data were collected during walking. The subject was asked to walk back and forth at a self-selected pace on a 10 meter carpet approximately 20 times. Data were collected before and after the training protocol. The curves, peak and excursion of moment were determined. The angle of the knee joint in three planes, GRF and force within the knee joint were compared. Balance and lower limbs functions were assessed by the Berg Balance Scale (BBS) and the Fugl-Meyer Assessment of the Lower Limb (FMA-LE) before and after training.

3. Result

3.1. Balance and lower limbs functions

Results showed the BBS score changed from 45/56 to 51/56. Increased scores were noted in items B11 to B14 (each having 2 points of turning 360 degrees and alternate foot on stool, and 1-point of tandem stance and standing on one leg). However, no change was observed in the FMA-LE scores

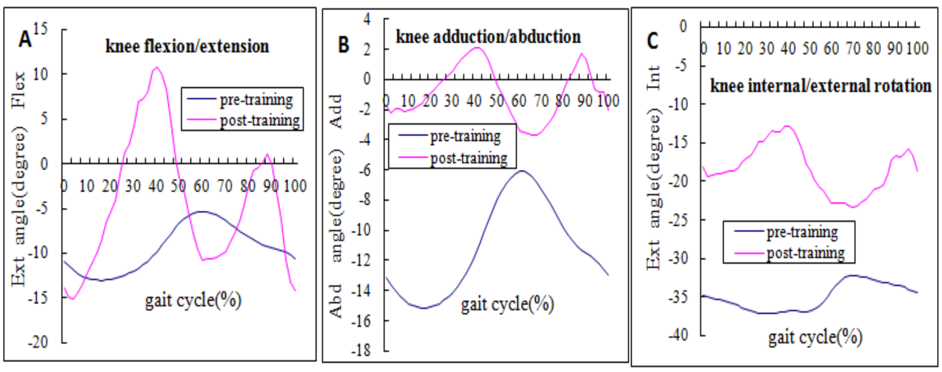

Fig. 2. Normalized gait cycle of the mean moment and angle of knee joint flexion/extension (A), adduction/abduction (B), and internal and external rotation (C). The profiles are intra-subject averages from our patient (n = 10 trails) during one gait cycle measured before (Blue line) and after 3 weeks of training (Red line). The moment is normalized to body weight (BW).

(from 32/34 to 32/34).

3.2. Kinematic and kinetic parameters

Pre-training and post-training knee movement trajectory and moment changes for stance phase and swing phase are shown in Figure 2. Increased in peak knee flexion (from -4.99° to 13.47°) and moment (from 0.18 Nm/kg to 0.20 Nm/kg) in the right knee joint after training were found (Figure 2). Knee extension peak moment decreased from 1.03 Nm/kg to 0.53 Nm/kg. Normalized right knee joint force and GRF decreased from 0.68 N to 0.45 N and from 11.06 N to 10.11 N respectively. The degree and moment of adduction and internal rotation of the right knee joint were also improved (Tables 2 and 3, Figure 2).

4. Discussion

4.1. Balance and lower functions

This case report described the changes in balance, kinetic and kinematic parameters in a subject after RKO gait training. She participated in the programme due to loss of knee flexion and pain during walking. Outcomes suggested that a combined RKO program with targeted intervention training led to improved gait pattern in terms of reducing knee hyperextension, knee moment, GRF and knee joint force while standing on the paretic lower extremity.

Four out of the 14 tasks on the BBS showed improvement after training. Previous study that used RKO combined gait training in stroke patients [13] had shown similar improvements in balance functions [14]. No improvement in lower limbs motor functions was observed in the FMA-LE score. This observation may be due to the primary focus of the RKO on dynamic balance and functional activities [12, 13], while Fugl-Meyer assessment focuses on the early therapeutic measures with hemiplegic patients [15]. Further investigations into muscle activity with electromyography and muscle strength changes are needed to determine exactly what role does RKO plays in neurorehabilitation.

Table 2

Clinical scales and knee joint kinematic results at baseline and post-intervention

	BBS	FMA-LE	Peak Degree (°)					
			Flex(+)/Ext(-)		**Add(+)/Abd(-)**		**Int(+)/Ext(-)Rot**	
			High	**Lower**	**High**	**Lower**	**High**	**Lower**
Baseline	45	32	-4.99	-13.10	-5.58	-15.20	-31.84	-37.67
Post-training	51	32	13.47	-16.47	4.05	-4.25	-11.64	-24.22

Table 3

Kinetic parameters at baseline and post-intervention of knee joint

	Moment (Nm/kg)						GRF	Force
	Flex(+)/Ext(-)		**Add(+/Abd(-)**			**Int(+)/Ext(-)Rot**	**(N)**	**(N)**
	High	**Lower**	**High**	**Lower**	**High**	**Lower**		
Baseline	0.18	-1.03	0.59	-0.07	0.07	-0.09	11.06	0.68
Post-training	0.20	-0.53	0.77	-0.05	0.09	-0.11	10.11	0.45

4.2. Kinematic and kinetic changes

Wong and coworkers and Byl investigated mobility training in patients with stroke using the RKO but did not include detailed kinematic and kinetic analysis of the knee joint [12, 13]. This subject exhibited an increase in peak knee flexion angle (from -4.99° to 13.47°) during the stance phase (Table 2) after 3 weeks of training with RKO. This finding is in line with kinematic analysis from stroke patients with genu recurvatum wearing an AFO, which showed a significant increase in peak knee flexion during the stance phase [16]. The trajectory in this case also showed another knee flexion during the swing phase, although the value was lower compared with the normal range (Figure 2B). This finding may be related to the motor control setting of the RKO between 5°-15° to limit knee extension, without restricting flexion during the stance and swing phase. Sulzer and coworkers used a powered knee orthosis that generated knee flexion torque assistance during pre-swing to treat stiff-knee gait (SKG) in persons with chronic stroke. The results demonstrated that training could increase pre-swing knee flexion. This approach is not suitable for knee joint muscle weakness in genu recurvatum [17]. Jagadamma and coworkers used AFO and wedges in people with cerebral palsy and knee hyperextension. Their results showed that knee hyperextension was corrected during the stance phase [10]. However, using an AFO in patients with knee hyperextension could not increase knee flexion during the swing phase [9]. In this current study, the knee extension angle was still present in the gait cycle, indicating that knee hyperextension was not totally resolved. It is understood that 3 weeks of training is not possible to return hamstring strength to normal in this limited period of time. In addition, the subject's abnormal knee joint movement had been reinforced by 3 years of walking with a habitual knee hyperextension gait. This would in turn impaire the hamstring muscles. Future studies with a longer training period are needed to verify the time effects of RKO training on correcting knee hyperextension.

The recovery of normal gait in the subject was evidenced with a decrease in the degree of external rotation of the knee and absence of circumductive gait. A hemiplegic gait pattern usually involves circumduction during the swing phase because of insufficient knee and ankle joint flexion [18]. Other rehabilitation interventions and approaches to correct circumductive gait have been published in the literature [17, 19]. RKO combined treadmill walking could increase knee flexion and hip abduction to facilitate foot clearance [17]. The Lokomat robot has been used to guide patients with stroke through a symmetric kinematic gait pattern to aid with foot clearance during the swing phase [19]. RKO provides dynamic assistive knee extension and resistive knee flexion. This current study also demonstrated RKO over-ground training leads to increased flexion and decreased external rotation of the knee joint, which in turn contributes to the clearance of circumductive gait.

The reduction of knee extensor moment in the paretic limb contributed to the correction of knee hyperextension in this study. This finding is similar to literature describing the use of orthosis and ambulation aids to assist patients with hemiplegia in correcting knee hyperextension by adjusting knee joint moment [16, 19, 20]. The use of knee AFO could decrease knee extensor moment and correct genu recurvatum during stance in patients with stroke [16]. The decrease in magnitude of the knee-extending moment could also reduce extension moment and therefore improve walking performance [20]. Lokomat improved paretic knee flexion torque during late stance and pre-swing phase to normalize gait pattern [19]. The mechanism of these changes may relate to the biomechanical properties of knee flexors and extensors as contribution to joint movement. Riley and Kerrigan used biomechanical models to study the torque action of the two-joint muscles in stiff-legged gait. Results showed that rectus femoris and hamstrings contribute primarily to knee moment rather than hip. The change in knee extension moment could play a key role in knee angle correction [21]. Resisted and isometric hamstring exercise, together with hamstring and quadriceps femoris isometric co-contraction exercises, have also been shown to help decrease knee extension moments and improve knee stability

[22]. Results in this study were in agreement with these studies. RKO provided resistive force to the hamstrings and assistive force to quadriceps femoris, and maintained the coordination of knee joint movement. Future studies are warranted to measure muscle strength and activation before and after training to improve understanding of the mechanism of muscle moment acting on joint motion.

Another goal of using the RKO was to decrease knee joint and tibialis anterior pain. Pain is a subjective and complex sensory experience, It is affected by cognitive and situational factors [23]. Gait analysis can offer an objective way to measure a patient's level of knee osteoarthritis pain. Published literature shows gait parameters (i.e. knee adduction moment) are relevant to osteoarthritis knee pain [24]. Sharma and coworkers investigated the dynamic loading of the knee by measuring the adduction moment. This group showed a direct correlation between the adduction moment and medial pain in a knee joint with osteoarthritis [25]. Similarly, after RKO training, the subject reported relief from knee joint and tibialis anterior pain along with a decrease in knee extension moment (Table 3). Literature suggested that correcting genu recurvatum could alleviate knee pain [26].

Published literature indicates that knee hyperextension impairment is characterized by a GRF vector that passes in front of the knee and generates a knee extensor moment to prevent collapse during stance phase [16, 27]. This case study found a decrease in the peak GRF as well as a decrease in the peak knee joint force (Table 3). This observation may explain why the subject felt relief of her pain at the paretic anterior tibia and knee joint after RKO training. Using a dedicated knee orthosis with 4° valgus has been reported to decrease knee loading more effectively than other degrees or no orthosis [28]. This study also found that after training, the subject had an adduction and abduction at around the 4° range (Table 2), which contributes to the reduction in pain with the wearable RKO during training.

5. Conclusion

The RKO provided co-contraction training between the quadriceps femoris and hamstrings through improving knee joint kinematic and kinetic parameters in conjunction with over-ground walking. This training decreased knee hyperextension, improved knee flexor and extensor moments, and alleviated pain. The use of RKO may therefore be clinically effective in gait recovery in patients with genu recurvatum as a result of damaged central nervous system.

Acknowledgment

This study is supported by the National Natural Science Foundation of China (No. 30973165, 31100669 and 81372108) and in part by Science and Technology Planning Project of Guangdong Province, China (No. 2013b090500099) and in part by Guangzhou Research Collaborative Innovation Projects (No. 2014Y2-00507).

References

[1] M. Ackermann and A.J. van den Bogert, Optimality principles for model-based prediction of human gait, Journal of Biomechanics **43** (2010), 1055–1060.
[2] T.P. Andriacchi, Dynamics of pathological motion: applied to the anterior cruciate deficient knee, Journal of Biomechanics **23** (1990), 99–105.
[3] K. Parvataneni, L. Ploeg, S.J. Olney and B. Brouwer, Kinematic, kinetic and metabolic parameters of treadmill versus overground walking in healthy older adults, Clinical Biomechanics **24** (2009), 95–100.

[4] C. Bleyenheuft, Y. Bleyenheuft, P. Hanson and T. Deltombe, Treatment of genu recurvatum in hemiparetic adult patients: A systematic literature review, Physical Rehabilitation and Medicine **53** (2010), 189–199.
[5] J.J. Knapik, C.L. Bauman, B.H. Jones, et al., Preseason strength and flexibility imbalances associated with athletic injuries in female collegiate athletes, American Journal of Sports Medicine **19** (1991), 76–81.
[6] R.E. Hogue and S. McCandless, Genu recurvatum: Auditory biofeedback treatment for adult patients with stroke or head injuries, Archives of Physical Medicine and Rehabilitation **64** (1983), 368–370.
[7] M.E. Morris, T.A. Matyas, T.M. Bach and P.A. Goldie, Electrogoniometric feedback: Its effect on genu recurvatum in stroke, Archives of Physical Medicine and Rehabilitation **73** (1983), 1147–1154.
[8] M.J. Killington, S.F. Mackintosh and M Ayres, An isokinetic muscle strengthening program for adults with an acquired brain injury leads to meaningful improvements in physical function, Brain Injury **24** (2010), 970–797.
[9] M.E. Busse, C.M. Wiles and R.W. Van Deursen, Co-activation: its association with weakness and specific neurological pathology, Journal of Neuroengineering and Rehabilitation **20** (2006), 26.
[10] K.C. Jagadamma, F.J. Coutts, T.H. Mercer, et al., Effects of tuning of ankle foot orthoses-footwear combination using wedges on stance phase knee hyperextension in children with cerebral palsy-preliminary results, Disability and Rehabilitation: Assistive Technology **4** (2009), 406–413.
[11] Y, Morinaka, Y, Matsuo, M, Nojima, et al., Biomechanical study of a knee ankle–foot-orthosis for hemiplegic patients, Prosthetics and Orthotics International **8** (1984), 97–99.
[12] N.N. Byl, Mobility training using a bionic knee orthosis in patients in a post-stroke chronic state: A case series, Journal of Medicine Case Report **6** (2012), 216–220.
[13] C.K. Wong, L. Bishop and J. Stein, A wearable robotic knee orthosis for gait training: A case-series of hemiparetic stroke survivors, Prosthetics and Orthotics International **36** (2012), 113–120.
[14] D. Donoghue, Physiotherapy Research and Older People (PROP) group and E.K. Stokes, How much change is true change? The minimum detectable change of the berg balance scale in elderly people, Journal of Rehabilitation Medicine **41** (2009), 343–346.
[15] A.R. Fugl-Meyer, L. Jaasko, I. Leyman, et al., The post-stroke hemiplegic patient, I. A method for evaluation of physical performance, Scandinavian Journal of Rehabilitation Medcine **7** (1975), 13–31.
[16] J. Boudarham, R. Zory, F. Genet, et al., Effect of a knee-ankle-foot orthosis on gait biomechanical characteristics of paretic and non-paretic limbs in hemplegic patients with genu recurvarum, Clinical Biomechanics **28** (2013), 73–78.
[17] J.S. Sulzer, K.E. Gordon, Y.Y. Dhaher, et al., Preswing knee flexion assistance is coupled with hip abduction in people with stiff-knee gait after stroke, Stroke **41** (2010), 1709–1714.
[18] C.L. Chen, H.C. Chen, S.F. Tang, et al., Gait performance with compensatory adaptations in patients with stroke with different degrees of motor recovery, American Journal of Physical Medicine & Rehabilitation **82** (2003), 925–935.
[19] N.D. Neckel, N. Blonien, D. Nichols and J. Hidler, Abnormal joint torque patterns exhibited by chronic stroke subjects while walking with a prescribed physiological gait pattern, Journal of NeuroEngineering and Rehabilitation **5** (2008), 19.
[20] S. Roehrig and D.A. Yates, Effects of a new orthosis and physical therapy on gait in a subject with longstanding hemiplegia, Journal of Geriatric Physical Therapy **31** (2008), 38–46.
[21] P. Riley and D. Kerrigan, Torque action of two-joint muscles in the swing period of stiff-legged gait a forward dynamic model analysis, Journal of Biomechanics **31** (1998), 835–840.
[22] Me Maitland, S.V. Ajemian and E. Suter, Quadriceps femoris and hamstring muscle function in a person with an unstable knee, Physical Therapy **79** (1999), 66–75.
[23] F. Cappellino, T. Paolucci, F. Zangrando, et al., Neurocognitive rehabilitation approach effectiveness after anterior cruciate ligament reconstruction with patellar tendon, a randomized controlled trial, European Journal of Physical and Rehabilitation Medicine **48** (2012), 17–30.
[24] J.L. Asay, K.A. Boyer and T.P. Andriacchi, Repeatability of gait analysis for measuring knee osteoarthritis pain in patients with severe chronic pain, Journal of Orthopaedic Research **31** (2013), 1007–1012.
[25] L. Sharma, D.E. Hurwitz, E.J. Thonar, et al., Knee adduction moment, serum hyaluronan level, and disease severity in medial tibiofemoral osteoarthritis, Arthritis & Rheumatology **41** (1998), 1233–1240.
[26] K. Nishitani, Y. Nakagawa, T. Suzuki, et al., Rotating-hinge total knee arthroplasty in a patient with genu recurvatum after osteomyelitis of the distal femur, Journal of Arthroplasty **22** (2007), 630–633.
[27] D.E. Hurwitz, A.R. Ryals, J.A. Block, et al., Knee pain and joint loading in subjects with osteoarthritis of the knee, Journal of Orthopaedic Research **18** (2000), 572–579.
[28] C.H. Pagani, C. Böhle, W. Potthast and G.P. Brüggemann, Short-term effects of a dedicated knee orthosis on knee adduction moment, pain, and function in patients with osteoarthritis, Archives of Physical Medicine and Rehabilitation **91** (2010), 1936–1941.