KNEE

Vertical ground reaction force and knee muscle activation asymmetries in patients with ACL reconstruction compared to healthy individuals

Zahed Mantashloo[1] · Amir Letafatkar[1] · Mohsen Moradi[1]

Abstract

Purpose Gait analysis is an important index in the clinical treatment of people with anterior cruciate ligament (ACL) injury. Following unilateral ACL reconstruction (ACLR), the knee kinetic asymmetries are likely to affect the gait cycle. Therefore, the aim of this study was to examine the symmetries of vertical ground reaction force (vGRF) and select the knee muscle activity in gait cycles in participants with and without unilateral ACLR.

Methods In this cross-sectional study, vGRF and muscle activity data in difference gait cycles were collected from 56 male subjects (28 with unilateral ACLR and 28 healthy subjects) using force plate and electromyography (EMG), respectively. MATLAB software was used for data analysis and independent *t* test was employed to compare the two groups.

Results No significant difference was seen between the two groups in the variable of first peak force symmetry (n.s). However, there was a significant difference in the second-peak force symmetry index between the two groups ($p \leq 0.001$). Regarding muscle activity symmetry in the braking phase of gait, a significant difference was observed in rectus femoris between the two groups ($p \leq 0.001$), while no difference was seen in medial gastrocnemius and biceps femoris activity (n.s). In the propulsive phase of gait, there was a significant difference in medial gastrocnemius and biceps femoris muscles activity between the two groups ($p \leq 0.001$), while no difference was found in rectus femoris muscle activity (n.s).

Conclusions The results revealed that unilateral ACLR creates asymmetry in vGRF and muscle activities in different phases of the gait cycle. So, more attention should be paid to this problem in clinical settings, and also to the use of therapeutic interventions to reduce the amount of kinetic asymmetries.

Level of evidence III.

Keywords Gait analysis · Symmetry · Anterior cruciate ligament · Reconstruction · Electromyography

Introduction

In the absence of pathology, gait is a coordinated, efficient, and effortless activity, while any abnormality can affect the accuracy, coordination, speed, and adaptation [20]. Since the limbs must be in perfect coordination to achieve a smooth motion, the issue of gait symmetry is important [25]. On the other hand, because in many cases asymmetry is considered as a factor for gait abnormality, the results of studies that assume gait symmetry to interpret their own results have controversial issues [25, 30]. Therefore, providing a comprehensive and reliable method to achieve gait symmetry is an important concern for physicians and researchers.

In athletes with ACL rupture and ACLR, the biomechanical features of the lower limb change in comparison to healthy subjects [18, 27, 28]. In this regard, knee instability and degenerative changes appear in articular cartilage and meniscus [12, 16]. Patients with ACLR reconstruction use compensation strategies during lower limb movements to reduce the eccentric load and vGRF [1] which might be associated with changes in forces, muscle torque, and muscle activity in the sagittal plane [11, 24]. As a result, when patients try to perform symmetrical movements, they use an internal displacement pattern which tries to remove pressure from the muscles (for example, quadriceps) and

✉ Amir Letafatkar
letafatkaramir@yahoo.com

1 Department of Biomechanics and Sport Injury, Faculty of Physical Education and Sports Sciences, Kharazmi University, Tehran, Iran

transfer them to other muscles (such as hamstring) [26, 27] or attempts to transfer pressure from the injured foot to the healthy foot [27].

A possible method that can improve our understanding of the mechanism of gait coordination is testing the symmetric index [4]. Many studies have shown that the asymmetric index appears in many pathological conditions (leg length discrepancy [21], stroke [15], cerebral palsy [29], and Parkinson's disease [34]).

Many of the features can be extracted from GRF and muscle activity to distinguish between normal and abnormal behavior patterns [22]. As a result, the study of the symmetry of GRF and muscle activity in patients with ACLR seems important and necessary. However, the symmetry index (SI) in GRF and electromyography variables in patients with unilateral ACLR reconstruction in gait cycles is a less investigated area [9]. Therefore, the aim of this study was to examine the symmetry of vGRF (first and second peak) and selected knee muscle (Gastrocnemius (GC), rectus femoris(RF), and biceps femoris(BF)) activity in male subjects with and without unilateral ACL reconstruction gait cycles.

It was hypothesized that the subjects with unilateral ACL reconstruction would have asymmetry in vertical ground reaction force and knee muscle activation in gait cycles, compared to the healthy ones.

Materials and methods

In this cross-sectional study, after screening from the statistical population, 56 male subjects (28 subjects with ACLR and 28 healthy ones) volunteered to participate in this study. This study was approved by the Kharazmi University Institutional Review Board for ethic number DBSI10190322018.

Inclusion criteria were: (a) diagnosis of complete ACL rupture, with no severe or complex meniscus or collateral ligament damage or continued knee dysfunction; (b) subsequent unilateral ACLR; (c) no history of visual, vestibular, or neurological problems; (d) no complaint of knee pain; (e) ability to walk independently; (f); having a full knee joint range of motion; (g) passing at least 6 months of ACL surgery; (h) no usage of brace [2].

After referrals to the laboratory, the stages of testing and how variables are measured were explained for every subject, and the subjects completed the consent form for participating in the study. Then, each one was asked to wear their usual sports clothes to warm up. A force plate (Kistler model, Winterthur) placed in the walkway, was used to measure the vGRF data.

The subjects were asked to cross an 8 m path through the force plate. Subjects needed to place both feet on the force plate and cross it. They were asked to walk normally; if any

of the legs were not completely on the force plate, the test was repeated. The tests were repeated long enough to obtain three correct tests. The criteria considered included vGRF and time to vGRF.

The vGRF data were stored with a 500 Hz sampling rate on the computer by force plate. For filtering the data from the plate, the low-pass Butterworth filter was used. The residual analysis method was applied to determine the cut-off frequency [33]; for this study, the cut-off frequency was obtained as 10 Hz. The muscle activity was achieved through eight-channel electromyography (EMG) device (MIE) with a sampling rate of 1000 Hz. The distance between electrodes was 20 mm. The EMG raw signals were filtered using a band-pass filter of 10–450 Hz. The amount of muscle activity was analyzed by applying the root mean square method [22] using the following formula:

$$\mathrm{RMS}\{\mathrm{EMG}(t)\} = \left(\frac{1}{T} + \int_{t}^{t+T} \mathrm{EMG}^2(t)dt \right)^{1/2}.$$

In the initial contact phase and throughout the loading response phase, the vGRF increases with the body weight transfer from the back leg to the front leg. The maximum loading occurs in the first phase of the mid-stance phase because at this time the acceptance of body weight, as well as the increase in the muscular force occurred during the transfer from double support to single limb stance (first peak). When the knee extends at the mid-stance, the center of mass (COM) moves upward. Reduction in the COM acceleration occurs near its highest position, and this is a reason for the decline of vGRF less than the weight of the body. Then the vGRF is increased until the second peak at the end of the stance phase occurs (second peak) [17].

To record the EMG waves, the hair from their skin was removed and it was purified by isopropyl alcohol 5%. The electrodes were then attached to the GC, BF and RF to the right and left muscles using SENIAM method [10].

Each subject performed three walking movements. The rest time between the attempts was 1 min. The walking was divided into two phases: braking and propulsion, and the variables were calculated using MATLAB 2013. The vGRF data were normalized using the subjects' weight and muscles activity was normalized by maximum voluntary contraction. To obtain SI, the following formula provided by Robinson et al., [23] was used:

$$SI = 100 * (XR - XL/0.5 * (XR + XL)).$$

Statistical analysis

Using G*POWER software and independent t test with $\alpha = 0.05$, the medium effect size (0.68) and $\beta = 0.2$ (power = 0.80), 28 subjects were determined for each group.

Table 1 Mean and standard deviation of participants' demographics and characteristics

Groups	Age (years)	Height (cm)	Weight (kg)	BMI (kg/m^2)
ACL	23.7 ± 2.0	179.2 ± 8.2	78.1 ± 7.9	24.4 ± 1.6
Healthy	24.6 ± 2.4	177.8 ± 6.5	75.6 ± 8.5	24.0 ± 1.9
p value	n.s	n.s	n.s	n.s

n.s not significant

Shapiro–Wilk test was employed to assess the normal distribution of data. Independent *t* test was utilized to compare healthy and ACL groups. These analyses were performed using SPSS software version 22. In this study, the significance level was considered 0.05.

Results

There were no significant differences between the groups in terms of age (n.s), mass (n.s), height (n.s), or BMI (n.s) (Table 1).

The mean and standard deviation of vGRF and muscle activity in left and right limb are presented in Table 2.

The results of Table 3 indicated that there was no significant difference between the patients with unilateral ACLR and healthy subjects in the variable of the first peak force symmetry (n.s) with SI in the patients with unilateral ACLR (8.0) and in healthy subjects (5.9). However, there was a significant difference in the second-peak force between patients with unilateral ACLR and healthy subjects ($p \leq 0.001$) with SI in the patient with unilateral ACLR (16.2) and in healthy subjects (4.3) (Table 3).

There was no significant difference between patients with unilateral ACLR and healthy subjects in SI of activity of medial GC and BF in the braking phase (n.s), and the results showed no (n.s). The value of the medial GC muscle activity SI in the braking phase in the patients with unilateral ACLR and healthy subjects was 9.4 and 8.2, respectively. Also, the value of the BF muscle activity SI in the braking phase in the patient with unilateral ACLR and healthy subjects was 9.2 and 7.7, respectively (Table 4).

There was a significant difference in RF muscle activity in the braking phase between patients with unilateral ACLR

Table 2 Average and standard deviation of vGRF and muscle activity

Variable groups	vGRF		Muscle activity, %MVC					
	First peak	Second peak	Braking			propulsion		
			GC	RF	BF	GC	RF	BF
ACL reconstruction limb								
Mean	116.6	95.3	18.1	24.6	16.0	46.3	15.2	40.7
SD	19.7	16.1	4.9	6.8	3.8	8.5	3.7	9.7
ACL Healthy limb								
Mean	113.0	117.2	16.0	19.5	14.3	35.8	13.3	31.6
SD	17.8	19.2	5.1	4.9	4.1	5.1	3.2	8.0
Healthy right limb								
Mean	103.6	110.1	13.9	19.8	12.1	32.8	12.1	29.7
SD	16.5	15.5	4.2	4.8	4.0	5.7	3.1	6.8
Healthy left limb								
Mean	106.3	114.6	14.2	20.6	12.8	33.4	11.1	31.3
SD	17.3	16.3	4.3	5.3	4.3	5.0	2.3	6.3

vGRF vertical ground reaction force, *GC* gastrocnemius, *RF* rectus femoris, *BF* biceps femoris

Table 3 Comparison of the vertical ground reaction forces SI during gait between unilateral ACLR and healthy

Variable	Phase	Groups	M ± SD	T	p value	%95 Cl	
						Lower	Upper
SI of vGRF	First peak	ACL	5.3 ± 8.0	1.9	(n.s)	− 0.7	4.4
		Healthy	2.9 ± 5.9				
	Second peak	ACL	3.3 ± 16.2	16.1	0.000*	10.4	13.4
		Healthy	2.0 ± 4.3				

n.s not significant

*Significant difference between groups

Table 4 Comparison of the muscle activity SI during the braking phase of gait between unilateral ACLR and healthy

Variable	Phase	Groups	M ± SD	T	p value	%95 Cl	
						Lower	Upper
SI of muscle activity	GC	ACL	5.8 ± 9.4	0.9	(n.s)	− 1.3	3.7
		Healthy	3.0 ± 8.2				
	RF	ACL	5.5 ± 14.2	6.3	0.000*	5.3	10.2
		Healthy	3.5 ± 6.4				
	BF	ACL	4.6 ± 9.2	1.5	(n.s)	− 0.6	3.7
		Healthy	3.4 ± 7.7				

GC gastrocnemius, *RF* rectus femoris, *BF* biceps femoris, *n.s* not significant

*Significant difference between groups

and healthy subjects ($p \leq 0.001$) with a SI in the patient with unilateral ACLR and healthy subjects (14.2 and 6.4, respectively) (Table 4).

There was a significant difference in medial GC and BF muscles activity in the propulsive phase between the patients with unilateral ACLR and healthy subjects ($p \leq 0.001$). The medial GC SI in the patients with unilateral ACLR and healthy subjects was 12.5 and 4.2, respectively. the BF muscle SI in the patients with unilateral ACLR and healthy subjects was 15.1 and 5.0, respectively (Table 5).

On the other hand, there was no significant difference in RF muscle activity in the propulsive phase between patients with unilateral ACLR and healthy subjects (n.s) with SI in the patient with unilateral ACLR and healthy subjects (7.1 and 5.7, respectively) (Table 5).

Discussion

The most important finding of the present study obtained from comparing the unilateral ACLR patients with healthy subjects was the presence of asymmetry in vGRF (at the first peak), activity of GC and BF (at the braking phase), and activity of RF (at the propulsive phase of gait.

The results revealed that there was no significant difference between the participants with unilateral ACLR and healthy subjects in the variable of the first peak force

symmetry. However, there was a significant difference in the second-peak force SI between the participants with unilateral ACLR and healthy subjects.

Ellis et al. reported that gait asymmetry can enhance metabolic and mechanical expenditure. So, symmetrical walking has an impact on the optimal mode for healthy individuals [7]. As a result, achieving full walking symmetry is often an important target for physiotherapy of people with various diseases and functional abnormalities. Comparing GRFs in normal and pathologic patients, researchers in 2009 reported that there was a significant difference between normal subjects and patients with ACLR in the vGRF during walking [32]. Winiarski and Czamara compared the SI of normal and ACL-reconstructed individuals and reported that there was a significant difference between the two groups in the SI of step-length [31]. Several factors can alter the gait pattern in patients with ACLR. These factors include the consequences of ACL injury and the effects of the time of ACLR which exerts additional stress on the knee joint and changes the knee joint range of motion [5, 13].

The results of this study suggested that there was some asymmetry in the normal individuals in the vGRF and muscles activity, where the amount of asymmetry in the vGRF was below 6% while in the muscle activity it was approximately 4–8%. Zifchock et al. showed that healthy runners have different levels of symmetry in kinetic parameters [35]. The reason that may promote the movement of the trunk to

Table 5 Comparison of the muscle activity SI during the propulsive phase of gait between unilateral ACLR and healthy

Variable	Phase	Groups	M ± SD	T	p value	%95 Cl	
						Lower	Upper
SI of muscle activity	GC	ACL	4.6 ± 12.5	8.7	0.000*	6.3	10.1
		Healthy	1.9 ± 4.2				
	RF	ACL	3.9 ± 7.1	1.5	(n.s)	− 0.4	2.8
		Healthy	1.5 ± 5.7				
	BF	ACL	5.4 ± 15.1	8.1	0.000*	7.9	12.6
		Healthy	3.8 ± 5.0				

GC gastrocnemius, *RF* rectus femoris, *BF* biceps femoris, *n.s* not significant

*Significant difference between groups

the non-dominant limb is the presence of disturbance and displacement of the COP and predominance of the dominant limb [6]. Therefore, kinetic asymmetry causes more stress on one limb than on the other. The presence of asymmetry in human walking causes one of the lower limbs to reduce the function of the other limb.

At the end of the stance phase, vGRF grows until the second peak occurs. Increase in the second peak is due to pushing the foot in the opposite direction of the ground, thereby increasing the activity of plantar flexors and elevating the acceleration of COM when the body weight is transferred toward the front [17]. Therefore, effective muscle function is directly associated with the second peak force. In people with unilateral ACLR, the muscles are weaker and atrophic in the injured limb [12]. It can be concluded that muscle weakness in the injured limb reduces the acceleration of COM and second peak force [17]. Reduction of the second peak force on the injured limb also increases the asymmetry of the second peak in patients with ACLR.

The results of this study in SI of muscle activity at the braking phase showed that there was a significant difference in RF muscle SI between healthy subjects and those with unilateral ACLR, but there was no a significant difference in medial GC and BF. In the propulsive phase, there was no significant difference in RF muscle SI between the two groups, but the SI was significantly different in medial GC and BF. Bulgheroni et al. examined gait patterns 2 years after ACLR surgery and reported that there was no significant difference in muscle activity in these patients compared to healthy subjects. They reported that over time, the normal gait pattern would return again [3]. In this regard, Knoll et al. reported that the extent of BF muscle activity, in the pre-sowing phase after 4 months of surgery, was higher in subjects with ACLR than in healthy subjects [13]. Konish et al. reported that the volume of muscles was significantly lower in the limb with ACLR than in the healthy limb [14]. Therefore, it can be concluded that the muscles in the limb with ACL reconstruction are weaker and have to be more active than the healthy limb to produce a certain submaximal force [8]. In the braking phase, the RF muscle acts as eccentrically to maintain the body's weight. Due to the muscle weakness and atrophy in the injured limb, the RF muscle should be more active to the maintain body's weight [14], which can justify the asymmetry of the RF muscle in these patients.

Decreased muscle volume and knee joint laxity in people with ACLR cause these patients to transfer pressure from the injured knee to the hip joint. This occurs by reducing the knee extensor torque and increasing the hip extensor torque, using a compensatory strategy within the limb [19]. During the propulsion, BF muscle with its concentric contraction moves the hip to an extended position; in people with unilateral ACLR, due to inter-organizational compensatory

strategy, BF muscle has to be more active than healthy limb [26, 27]. Also, because of atrophy, the BF muscle tolerates more pressure, which makes it more active at the propulsion for progressive movement [14]. These factors can cause asymmetry in BF muscle in subjects with unilateral ACLR during propulsion. In the propulsive phase, GC muscle moves progressively with its active action. Since in people with unilateral ACLR, the volume of this muscle is lower than that of the healthy muscle, therefore, this muscle has less potential to produce force relative to its healthy counterpart [14]. Therefore, at the propulsion, GC muscle on the injured side has to be more active in moving forward, which can lead to asymmetry in the GC muscle in people with unilateral ACLR.

There were several key limitations in this study. The most important limitation was the failure to perform the kinematic evaluation of joints' movements, which could support the comprehensiveness of this research. The next limitation was not recruiting female subjects in the present study and comparing data obtained from both genders. In addition, the subjects participated in a walking task, so further research emphasizing more complex movements such as running, cutting, and jumping are required.

Orthopedic surgeons, corrective exercise/biomechanics specialists as a conditioning coach, health providers and researchers should pay careful attention to this problem in clinical setting, and for selecting the therapeutic interventions to reduce the amount of asymmetry in vGRF and muscles activity.

Conclusion

The results of this study revealed that unilateral ACLR creates asymmetry in vGRF in the second peak, the RF muscle in the braking phase, and BF and GC muscles in the propulsive phase. Therefore, due to the role of the knee muscles in movement control of the lower extremity, restoring the symmetry in the vGRF and activation of knee muscles are necessary for unilateral ACLR.

Compliance with ethical standards

Conflict of interest The authors report no conflict of interest.

Ethical approval This study was approved by the Kharazmi University Institutional Review Board.

References

1. Baumgart C, Schubert M, Hoppe MW, Gokeler A, Freiwald J (2017) Do ground reaction forces during unilateral and bilateral movements exhibit compensation strategies following ACL reconstruction? Knee Surg Sports Traumatol Arthrosc 25(5):1385–1394

2. Bjornaraa J, Di Fabio RP (2011) Knee kinematics following ACL reconstruction in females; the effect of vision on performance during a cutting task. Int J Sports Phys Ther 6(4):271–284

3. Bulgheroni P, Bulgheroni MV, Andrini L, Guffanti P, Giughello A (1997) Gait patterns after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 5(1):14–21

4. Carpes FP, Mota CB, Faria IE (2010) On the bilateral asymmetry during running and cycling review considering leg preference. Phys Ther Sport 11(4):136–142

5. Czamara A (2010) Evaluation of physiotherapeutic procedures after ACL reconstruction in males. Arch Bud 6(2):73–81

6. De-Cock A, Vanrenterghem J, Willems T, Witvrouw E, De Clercq D (2008) The trajectory of the center of pressure during barefoot running as a potential measure for foot function. Gait Posture 27(4):669–675

7. Ellis RG, Howard KC, Kram R (2013) The metabolic and mechanical costs of step time asymmetry in walking. Proc R Soc Proc Biol Sci 280(1756):1–7

8. Ferber R, Osternig LR, Woollacott MH, Wasielewski NJ, Lee JH (2002) Gait mechanics in chronic ACL deficiency and subsequent repair. Clin Biomech 17(4):274–285

9. Gardinier ES, Manal K, Buchanan TS, Snyder-Mackler L (2012) Gait and neuromuscular asymmetries after acute ACL rupture. Med Sci Sports Exerc 44(8):1490–1496

10. Hermens DH, Feriks B (2005) Surface electromyograghy for the non-invasive assessment of muscle (Seniam). http://www.seniam.org/pdf/contents8.PDF

11. Hurd WJ, Snyder-Mackler L (2007) Knee instability after acute ACL rupture affects movement patterns during the mid-stance phase of gait. J Orthop Res 25(10):1369–1377

12. Jomha NM, Borton DC, Clingeleffer AJ, Pinczewski LA (1999) Long term osteoarthritic changes in anterior cruciate ligament reconstructed knees. Clin Orthop Relat Res 358:188–193

13. Knoll Z, Kiss RM, Kocsis L (2004) Gait adaptation in ACL deficient patients before and after anterior cruciate ligament reconstruction surgery. J Electromyogr Kinesiol 14(3):287–294

14. Konishi Y, Ikeda K, Nishino A, Sunaga M, Aihara Y, Fukubayashi T (2007) Relationship between quadriceps femoris muscle volume and muscle torque after anterior cruciate ligament repair. Scand J Med Sci Sports 22(6):791–796

15. Lin PY, Yang YR, Cheng SJ, Wang RY (2006) The relation between ankle impairments and gait velocity and symmetry in people with stroke. Arch Phys Med Rehabil 87(4):562–568

16. Lundberg M, Thuomas KA, Messner K (1997) Evaluation of knee-joint cartilage and menisci 10 years after isolated and combined ruptures of the medial collateral ligament: investigation by weight-bearing radiography, MR imaging and analysis of proteoglycan fragments in the joint fluid. Acta Radiol 38(1):151–157

17. Marasovic T, Cecic M, Zanchi V (2009) Analysis and interpretation of ground reaction forces in normal gait. WSEAS Trans Syst 8(9):1105–1114

18. Paterno MV, Ford KR, Myer GD, Heyl R, Hewett TE (2007) Limb asymmetries in landing and jumping 2 years following anterior cruciate ligament reconstruction. Clin J Sport Med 17(4):258–262

19. Paterno MV, Schmitt LC, Ford KR, Rauh MJ, Myer GD, Hewett TE (2011) Effects of sex on compensatory landing strategies upon return to sport after anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther 41(8):553–559

20. Perry J, Burnfield JM (2010) Gait analysis: normal and pathological function, 2nd edn. Slack Incorporated, USA

21. Perttunen J, Anttila E, Sodergard J, Merikanto J, Komi P (2004) Gait asymmetry in patients with limb length discrepancy. Scand J Med Sci Sports 14(1):49–56

22. Robertson G, Caldwell G, Hamill J, Kamen G, Whittlesey S (2013) Research methods in biomechanics, 2nd edn. Human Kinetics, USA

23. Robinson RO, Herzog W, Nigg BM (1987) Use of force platform variables to quantify the effects of chiropractic manipulation on gait symmetry. J Manip Physiol Ther 10(4):172–176

24. Rudolph KS, Eastlack ME, Axe MJ, Snyder-Mackler L (1998) Movement patterns after anterior cruciate ligament injury: a comparison of patients who compensate well for the injury and those who require operative stabilization. J Electromyogr Kinesiol 8(6):349–362

25. Sadeghi H, Allard P, Prince F, Labelle H (2000) Symmetry and limb dominance in able-bodied gait: a review. Gait Posture 12(1):34–45

26. Salem GJ, Salinas R, Harding FV (2003) Bilateral kinematic and kinetic analysis of the squat exercise after anterior cruciate ligament reconstruction. Arch Phys Med Rehabil 84(8):1211–1216

27. Sanford BA, Williams JL, Zucker-Levin A, Mihalko WM (2016) Asymmetric ground reaction forces and knee kinematics during squat after anterior cruciate ligament (ACL) reconstruction. Knee 23(5):820–825

28. Vairo GL, Myers JB, Sell TC, Fu FH, Harner CD, Lephart SM (2008) Neuromuscular and biomechanical landing performance subsequent to ipsilateral semitendinosus and gracilis autograft anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 16(1):2–14

29. White R, Agouris I, Fletcher E (2005) Harmonic analysis of force platform data in normal and cerebral palsy gait. Clin Biomech 20(5):508–516

30. Whittle MW (2007) Gait analysis: an introduction, 4th edn. Butterworth-Heinemann Elsevier, Edinburgh

31. Winiarski S, Czamara A (2012) Evaluation of gait kinematics and symmetry during the first two stages of physiotherapy after anterior cruciate ligament reconstruction. Acta Bioeng Biomech 14(2):91–100

32. Winiarski S, Rutkiwska-Kucharska A (2009) Estimated ground reaction force in normal and pathological gait. Acta Bioeng Biomech 11(1):53–60

33. Winter DA (2009) Biomechanics and motor control of human movement. John Wiley & Sons, New Jersey

34. Yogev G, Plotnik M, Peretz C, Giladi N, Hausdorff JM (2007) Gait asymmetry in patients with Parkinson's disease and elderly fallers: when does the bilateral coordination of gait require attention? Exp Brain Res 177(3):336–346

35. Zifchock RA, Davis I, Hamill J (2006) Kinetic asymmetry in female runners with and without retrospective tibial stress fractures. J Biomech 39(15):2792–2797