



Methodology of gait assessment for identifying mechanisms of decompensatory musculoskeletal fatigue in patients with hip arthritis

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Abstract

Introduction Gait analysis is an objective tool for assessing treatment results and musculoskeletal function in patients with orthopedic pathology. Safety of compensatory mechanisms and the fatigue component seen with repeated measurements and being dependent on the clinical situation are essential for the patients.

The **objective** was to develop a methodology of gait assessment for identifying mechanisms of decompensatory musculoskeletal fatigue in patients with hip arthritis including those with THA of the contralateral limb.

Material and methods The study included 41 patients with Kellgren – Lawrence grade III and IV hips. Gait analysis was performed using the Stedis-Step treadmill and five Neurosens inertial sensors (Neurosoft LLC, Ivanovo, Russia), recording the spatiotemporal and kinematic characteristics of movements in the lumbosacral spine, hip and knee joints being synchronized with the step cycle. Patients were divided into two groups according to gait assessment protocol including Group 1 ($n = 26$) with three series of two-minute tests with a break of at least 20 minutes; Group 2 ($n = 15$) with three series of two-minute walks without a break with the total length of six minutes.

Results A 20-minute rest was enough to reproduce baseline gait parameters. Walking parameters including maximum flexion phase, stance period and range of motion could serve as markers for early detection of mechanisms of decompensatory muscle fatigue. The total hip arthroplasty on the contralateral side significantly affected the gait parameters.

Discussion New methods of no-break gait assessment facilitated decompensation and fatigue mechanisms identified in patients with hip arthritis. Reduced movement amplitude during short-term load indicated increasing fatigue even over a brief period (6 minutes).

Conclusion The methodology allowed for the identification of mechanisms of decompensatory musculoskeletal fatigue in patients with hip arthritis including those with THA of the contralateral limb, early diagnosis, improved monitoring and rehabilitation.

Keywords: gait analysis, decompensatory reaction, fatigue, hip arthritis, methodology, Stedis

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INTRODUCTION

Hip arthritis (HA) is a serious medical condition which can lead to significant medical and social challenges including impaired daily-life gait and quality of life [1, 2]. The incidence of osteoarthritis of the hip is constantly increasing and can be associated with increased life expectancy and a sedentary lifestyle [3]. Expanding surgical indications may be associated with the improved safety and technical variety that would improve quality of life and neuropsychological status of patients [4, 5]. The number of patients requiring revision total hip replacement (THR) who had undergone primary THR some 10–15 years ago is growing progressively. There are non-standardized approaches to diagnosis, selection of the optimal time for surgical treatment and objectification of the effectiveness of rehabilitation of this cohort of patients. Gait analysis is one of the most accurate and objective tools for assessing treatment results and an integral characteristic of function and activity for orthopedic patients [6, 7, 8].

Modern studies demonstrate that a multidisciplinary approach to the management of hip arthritis provides significant clinical results [9, 10]. The effectiveness would depend on the accurate assessment of individual compensatory capabilities of the musculoskeletal system and the reproducibility in multicenter, multidisciplinary management of the patient. The analysis of biomechanical disorders is essential for patients with HA and combined pathology, in the presence of the contralateral THR, in particular. Despite the available publications on gait analysis, clinical recommendations (Objective assessment of walking function: clinical guidelines https://rehabrus.ru/Docs/2017/02/Hodba_met_rek_pr_fin.pdf) and theoretical developments of the main biomechanical phenomena [11, 12], there are several fundamental problems:

- lack of uniform standards for conducting load tests;
- significant influence of fatigue factor on the results of repeated measurements of the gait biomechanics;
- insufficiently considered role of adjacent segments (pelvis, spine, knee joints) in compensating for the motor deficit of the hip.

The safety margin of compensatory mechanisms and the fatigue component are important for repeated measurements, which can vary significantly depending on the clinical situation. Traditional assessment methods may not allow for a quantification of the critical parameter, which significantly influences the effectiveness and volume of medical interventions, the process of patient recovery, his/her personalized biomechanical portrait and prognosis for recovery [13]. Restoration of the walking function, as a key goal of orthopedic interventions, requires objective criteria of effectiveness. Technologies that would facilitate structural and functional restoration without formation of pathological motor compensations are essential to pursue the goal. Inertial sensor technology as one of the ways of objective gait assessment can be introduced into clinical practice. The method suggests the use of static parameters and dynamics in changed motor stereotypes under weight-bearing, treatment and correction in real time, which is especially important for predicting the effectiveness, timeliness and optimal volume of treatment and rehabilitation. In this case, the use of inertial sensors plays a key role, allowing us to identify movement patterns in HA patients providing a more accurate assessment of the functionality [14, 15, 16].

The **objective** was to develop a methodology of gait assessment for identifying mechanisms of decompensatory musculoskeletal fatigue in patients with hip arthritis including those with THA of the contralateral limb.

MATERIAL AND METHODS

The study was conducted between January and March 2025 at the Pirogov Clinic of High Medical Technologies, St. Petersburg State University. The walking pattern was assessed using the Steadis-Step walking simulator and biofeedback (Neurosoft LLC, Ivanovo) in the Assessment configuration (RU No. RZN 2018/7458 dated 07.08.2018). Five Neurosens inertial sensors were used to be placed on the lumbosacral spine and on symmetrical areas of the middle third of the femurs and tibiae 2 cm above the lateral ankles (Fig. 1). The patient was asked to walk on a flat surface for two minutes at a comfortable pace.

The analysis of standard parameters automatically entered into the gait analysis protocol with the software included:

- temporal parameters of walking (step cycle (SC), step, step frequency); (цикл шага (ЦШ), шаг, частота шага);
- phases of the gait (support period, single support, double support, first double support, second double support, beginning of second double support, stride time);
- spatial parameters of the gait (height of the foot rise, circumduction — the distance from the central line of the walking direction to identical points of the foot in the frontal plane, half of the step base);
- hip flexion/extension (flexion/extension range, maximum extension phase, maximum extension, maximum flexion phase, maximum flexion);
- adduction/abduction in the hip joint (amplitude of adduction/abduction, phase of maximum abduction, maximum abduction, phase of maximum adduction, maximum adduction);
- hip rotation (rotation amplitude, phase of maximum external rotation, maximum external rotation, phase of maximum internal rotation, maximum internal rotation);
- kinematic parameters of the pelvis: adduction/abduction, flexion/extension, rotation.



Fig. 1 An instance of inertial sensors placed for patient examination

Considering the significance of the decreased support function of the hip joint with degenerative changes in the joint, goniograms and kinematic parameters synchronized with the walking pattern of the hip joint (the diseased and intact sides) were additionally analyzed during the support period (up to 50 % of the SC with a measurement step of 5 % of the SC). The study included 41 patients with Kellgren–Lawrence grade III and IV hips admitted to the trauma and orthopaedic department for elective treatment using THR. Preoperative examination was performed for the patients. Radiographs were provided using a digital radiography system with automatic image stitching SG Jumong retro (Korea). Exclusion criteria included patients with acute and/or chronic diseases of various etiologies in the acute stage. A comprehensive prospective examination was performed for THR patients using an objective gait function assessment technology based on inertial sensors.

A method of interval and continuous testing lasting six minutes was used to analyze the biomechanical aspects of the gait and identify the presence of specific fatigue changes in movement. The effect of THR on biomechanical indicators in hip arthritis was assessed. The patients were randomly divided into two groups. The gait analysis was performed in three series in group 1 ($n = 26$) with a standard protocol of two minutes each with a break between tests (rest) of at least 20 minutes. The gait analysis was also performed in three series in group 2 ($n = 15$) with a standard protocol of two minutes each, with a total examination time of six minutes. The groups were comparable in terms of gender and age composition, which allowed comparison of the data obtained (Table 1).

Table 1

Characteristics of study groups

Description		Values by groups	
		Group 1 ($n = 26$)	Group 2 ($n = 15$)
Mean age, years		58.23 ± 14.78	59.93 ± 14.85
Males	abs.	15	6
	%	58	40
Females	abs.	11	9
	%	42	60
Unilateral HA	abs.	15	10
	%	58	67
Bilateral HA	abs.	5	1
	%	19	6
Presence of contralateral THR	abs.	6	4
	%	23	27

Statistical processing of the variables was performed using the IBM SPSS Statistics v/23.0 program. The Shapiro – Wilk test was used to identify normal distribution of the quantitative data. The results showed that all data arrays corresponded to the normal distribution, which allowed the parameters to be used for further analysis. The reliability of differences was assessed using the Student's t-test (for independent and dependent groups) and the Spearman's rank correlation test was employed to identify correlation relationships between the parameters. The reliability level was taken as $\alpha = 0.05$. The results were presented as $M \pm \sigma$, where M was the arithmetic mean with σ being the standard deviation of the sample.

The study was performed in accordance with ethical principles for medical research involving human subjects stated in the Declaration of Helsinki developed by the World Medical Association in 1964, Federal Law dated 21.11.2011, No. 323 “On the Fundamentals of Health Protection of Citizens in the Russian Federation”, Federal Law dated 27.07.2006 No. 152 “On Personal Data”.

RESULTS

The spatial-temporal parameters of gait showed no significant differences in non-weight-bearing parameters for the patients in the series (Table 2), which is consistent with the previous assumption about a good compensatory adaptation corridor in trauma and orthopedic patients. Significant differences in the support period were determined due to single support, a decrease in rotation on the side of the involved joint and an earlier phase of maximum flexion, which generally reflect the mechanisms of compensatory unloading of the involved limb to reduce the support load on it.

Table 2

Spatiotemporal parameters of the step cycle and hip joint kinematics

Spatiotemporal parameters	Involved limb	Intact limb
Step cycle, s (SC)	1.24 ± 0.16	
Step, s	0.63 ± 0.09	0.61 ± 0.08
Step frequency, s/min	49.20 ± 0.05	
Support period, % SC	$63.79 \pm 3.87^{**}$	66.77 ± 3.71
Single support, % SC	$33.17 \pm 3.66^{**}$	36.13 ± 3.81
Double support, % SC	3.63 ± 6.73	30.63 ± 6.75
Beginning of the second double support, % SC	48.98 ± 2.43	50.95 ± 2.43
Height of foot rise, cm	11.20 ± 2.60	11.83 ± 2.19
Circumduction, cm	3.02 ± 1.39	3.24 ± 1.39
Flexion/extension range, °	54.15 ± 8.05	55.00 ± 9.32
Maximum extension phase, % SC	89.17 ± 21.71	89.20 ± 23.23
Maximum extension, °	7.41 ± 5.01	6.44 ± 5.27
Maximum flexion phase, % SC	$69.34 \pm 3.54^{**}$	72.76 ± 2.99
Adduction/abduction amplitude, °	8.85 ± 3.71	10.10 ± 3.29
Maximum adduction/abduction phase, % SC	66.46 ± 19.85	64.32 ± 21.30
Rotation amplitude, °	$11.29 \pm 3.52^*$	13.39 ± 4.91

Note: the reliability of differences between the involved and intact limbs demonstrated: * $p \leq 0.05$, ** $p \leq 0.01$

The analysis of the kinematic measurements of the hip flexion/extension in group 2 (without an interval between examinations) on the side of the hip arthritis, the flexion significantly decreased from the first to the third measurement suggesting progressive fatigue or pain. The indicators on the contralateral side, being primarily higher, also decrease by the third measurement, which might be a manifestation of compensatory overload (Fig. 2a). The initial flexion values on the involved side were higher in group 1 (interval walking with rest) with the hip extension increased by the third measurement suggesting that rest was ineffective as a long-term restorative measure for walking function. The decrease in the initial amplitude on the contralateral side was not accompanied by significant fatigue manifestations similar to those identified in the previous group, that is, a slowdown in the progression of fatigue was noted (Fig. 2b).

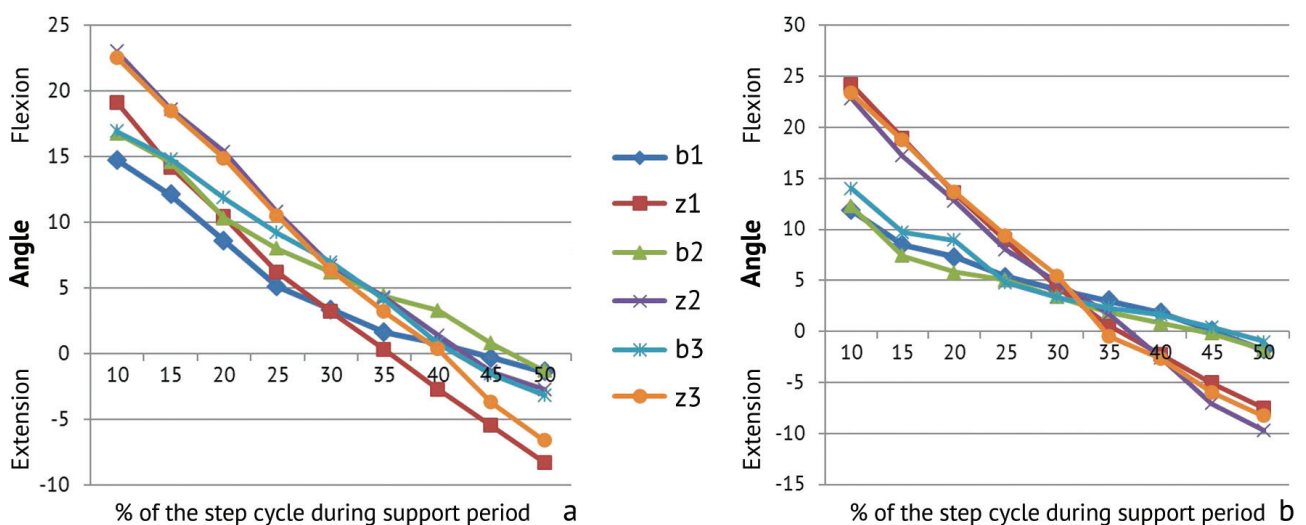


Fig. 2 Dynamics in flexion (positive values) and extension (negative values) values in the step cycle: (a) in group 2; (b) in group 1. Note: b1, b2, b3 are values for the involved lower limb for the first, second and third examinations; z1, z2, z3 are values for the intact lower limb for the first, second and third examinations

The analysis of the kinematic parameter adduction/abduction in group 2 (without interval rest) showed a progressive increase in the amplitude on the side of the involved joint ($b1 = 3.70$; $b3 = 6.65$; $p < 0.05$) suggesting compensatory hypermobility. A decrease in values could be observed on the intact side ($z1 = 3.90$; $z3 = 1.65$; $p < 0.05$), reflecting adaptive mechanisms for gait stabilization (Fig. 3a). In group 1 (interval rest), on the painful side the range of motion increases, possibly due to a temporary decrease in pain intensity, while on the contralateral side we observe a decrease in values. The range of motion increased on the involved side in group 1 (interval rest), possibly due to a temporary decrease in pain intensity and decreased values were noted on the contralateral side. This might indicate a redistribution of the load to symmetrize the walking pattern, which indicated a universal “rule of optimal gait” with synergistic interaction of muscles (Fig. 3b).

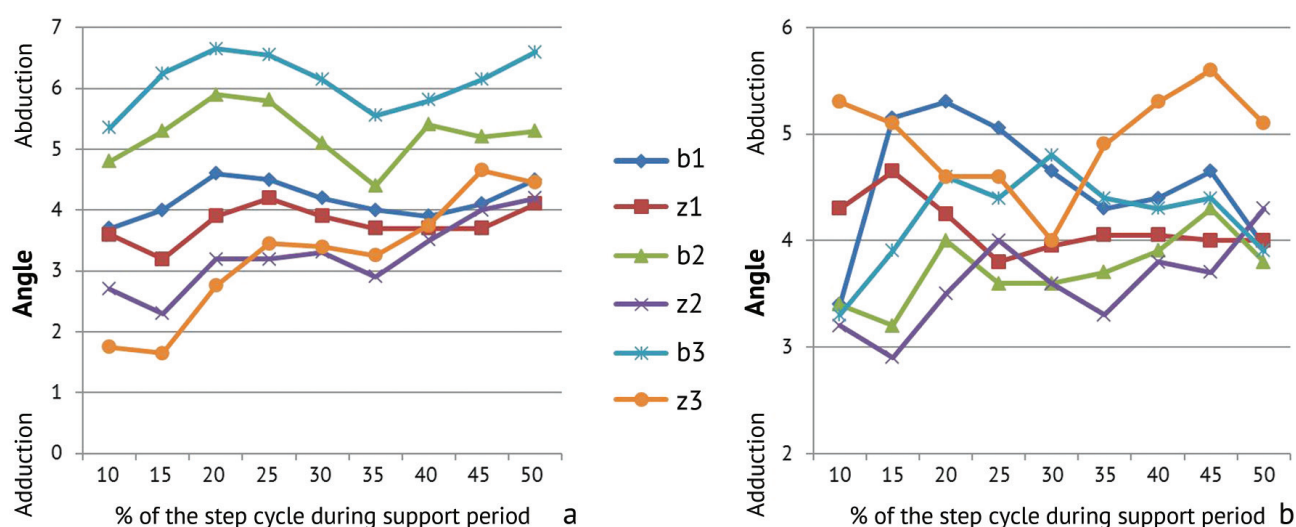


Fig. 3 Dynamics in adduction (positive values) / abduction (negative values) values in the step cycle: (a) in group 2; (b) in group 1. Note: b1, b2, b3 are values for the involved lower limb for the first, second and third examinations; z1, z2, z3 are values for the intact lower limb for the first, second and third examinations

Thus, the presence of interval rest did not allow us to identify subtle compensation mechanisms and the fatigue contribution of ultimate stress in hip arthritis. Walking parameters were compared in group 2 (without interval rest) separately in patients with and without contralateral THR to identify fatigue decompensation, additionally dividing the group into two subgroups: with contralateral THR ($n = 4$) and without contralateral THR ($n = 10$) (Table 3).

The analysis of the results showed the decreased support period in the subgroup of THR patients, while the pelvic flexion/extension indices (the higher hierarchical level of compensation) remained stable indicating a more uniform distribution of the load. The amplitude of adduction/abduction during walking remained unchanged, which indicated stability of movements. The support period increased in the subgroup without contralateral THR with no changes in the amplitude of flexion/extension of the pelvis during movement, which might indicate compensatory overload of the musculoskeletal system with repeated loads. Adaptive patterns were manifested in the increased phase of maximum flexion. It was suggested that the revealed phenomena were a manifestation of the systemic nature of the hip arthritis and limited compensation reserves of the contralateral limb. Additionally, flexion/extension, abduction/adduction and rotation of the hip joint were analyzed in patients with and without contralateral THR based on the results of the analysis of the walking in group 2 (without interval rest) (Fig. 4). Lower values of flexion/extension amplitude were observed during walking in the presence of the contralateral THR.

Table 3

Gait parameters in patients of group 2 (without interval rest)
depending on the presence of THR on the contralateral side

Parameters of the automatic gait analysis protocol	Measurement 1			Measurement 2			Measurement 3		
	With THR (n = 4)	Without THR (n = 10)	p < 0,05	With THR (n = 4)	Without THR (n = 10)	p < 0,05	With THR (n = 4)	Without THR (n = 10)	p < 0,05
Support period, difference, %	1.88	3.43	–	1.73	4.21	+	1.50	3.25	+
Single support, difference, %	1.75	3.52	+	1.38	4.10	+	1.53	3.25	–
Double support, difference, %	1.28	3.11	–	1.30	2.96	+	1.20	2.25	+
Stride period, difference, %	1.88	3.43	–	1.73	4.16	+	1.50	3.25	+
Maximum flexion phase, difference, %	2.00	3.50	+	1.75	4.20	+	1.75	3.00	+
Pelvis (involved side), flexion/extension, °	5.00	9.10	+	4.75	9.70	+	4.50	9.00	+
Pelvis (contralateral side), flexion/extension, °	5.00	8.80	+	4.50	9.40	+	4.50	9.00	+
Adduction/abduction, difference, °	0.00	0.50	+	0.25	0.20	–	0.00	0.00	–

Note: difference, between the right and left lower limbs; %, of the step cycle duration.

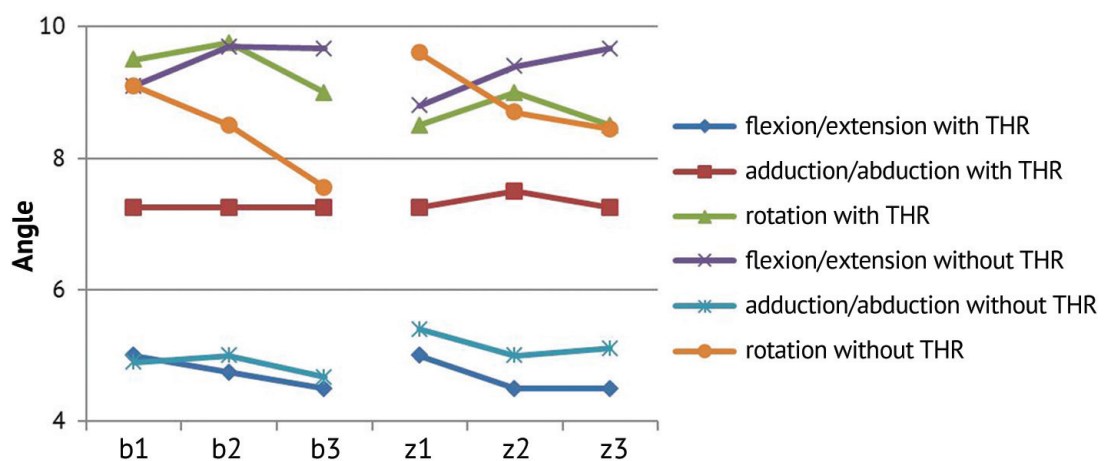


Fig. 4 Dynamics in the hip flexion/extension, adduction/abduction and rotation in the step cycle without interval rest between examinations: b1, b2, b3 are values for the involved lower limb for the first, second and third examinations; z1, z2, z3 are values for the intact lower limb for the first, second and third examinations

DISCUSSION

New treatment methods being developed and introduced into clinical practice are increasing the importance of the search and innovative means to be applied for objective outcome evaluation. Visualization of the dynamics and objective analysis of the walking function allows for a more accurate assessment of the impaired movement function in the dynamics using different technologies for conservative and orthopedic treatment of patients with HA, starting from the early stages of the disease [17, 18].

Ibara et al. suggested that objective assessment of movement function in patients with hip osteoarthritis could be produced without wearable sensors using only force platform data [14]. This approach is simple and fast, but it is limited to measuring reactive forces only and does not allow obtaining information about the kinematics of movements in the musculoskeletal system

as a whole, in all the variety of compensatory mechanisms included, in changes in joint angles, speeds and trajectories of limb movements, and inclusions of higher hierarchical levels. The use of wearable sensors facilitates simultaneous measurements of the kinematics and spatiotemporal parameters of walking providing a more complete understanding of gait patterns and allows for a more accurate analysis of motor functions. Therefore, wearable/inertial sensors are preferable for a comprehensive assessment of motor activity.

The findings suggest that gait analysis using inertial sensor technology is reproducible in multicenter studies, and the presence of rest between individual examinations does not affect the objective biomechanical parameters of the gait pattern with the rest of at least 20 min. The reproducibility of gait parameters using inertial sensor technology was reported in other studies of healthy people and patients with mobility impairments [12, 19, 20]. The methodology used in the study for assessing gait without interval rest with three series of walking analysis allows us to identify key features of decompensatory and fatigue mechanisms in patients suffering from hip arthritis. The use of multiple inertial sensors in combination with the proper placement is a promising approach for fatigue recognition and movement safety monitoring [21]. The available machine learning models can detect fatigue-related changes in gait, for example, based on ground reaction data from young healthy individuals running [22]. However, such models, trained on small samples and in narrow conditions, are not suitable for patients with hip osteoarthritis, as movements can vary greatly. Studies on larger samples are required to allow the use of the models in a clinic, taking into account all input parameters, that is, the models should be refined and retrained in groups of such patients. The promising approach is confirmed by the use of machine learning for the diagnosis of hip osteoarthritis using gait parameters [23]. A decreased amplitude of motion in the joints during the analysis of walking without rest between measurements indicates an increase in fatigue compensatory processes of the musculoskeletal system, even with short-term (six minutes in total) loads, sufficient to detect the depletion of the body's resources and requiring compensation.

Davis-Wilson et al. reported “an increase in forward trunk tilt on the side of osteoarthritis and a bilateral reduction in step length” detected with a six-minute walk test which was associated with compensatory mechanisms caused by pain, while the authors did not mention fatigue mechanisms of influence [24]. The authors reported the decreased walking speed being associated with pain, without the possibility to assess the fatigue component [25]. The contralateral limb with an intact joint, being an equivalent part of the single biomechanical chain of the musculoskeletal system of the lower limbs, is also involved in the compensation process, which manifests itself in signs of functional overload with a “vicious circle” being launched, increasing the asymmetry of the gait and reducing the effectiveness of the compensatory mechanisms. Hulet et al. reported the use of an optoelectronic system to identify gait asymmetry and compensatory mechanisms to be associated with pain in the involved joint and limited movement in the patient's hip joint and in the ipsilateral knee and ankle joints [26]. Van Rossom et al. reported no overload of the contralateral joint and ipsilateral knee joint in patients with hip osteoarthritis walking up stairs suggesting the specificity of compensatory strategies in different conditions and types of activities [27]. Adaptation of movements associated with fear of movement due to pain during walking can help patients reduce pain that can lead to restructuring of the entire pattern due to other levels of the musculoskeletal system [27, 28]. Maezawa et al. suggested that a difference in the lower limb length of 20 mm has little effect on walking patterns indicating the presence of universal

working compensatory mechanisms in the absence of severe deformity [29]. Compensation for leg length discrepancy occurs because the shortened lower limb is lengthened by “greater hip and knee extension, hip abduction, ankle plantar flexion, and less hip adduction”, and the other lower limb is shortened “due to higher flexion at the hip and knee joints, higher adduction of the hip, dorsiflexion and lower adduction of the ankle joint” [30]. We found no studies reporting the effect of THR on fatigue mechanisms during walking. Langley et al. showed that normal motor activity can be restored in patients with THR with high function [31].

We report lower values of the flexion/extension amplitude during walking in our series in the presence of the contralateral THR. Such indicators rather reflect the stabilization of biomechanics, the stability, rather than deterioration of function. In our opinion, the presence of the contralateral THR can limit excessive movements, preventing hypermobility and overload on the involved and intact sides in the presence of THR without the inclusion of the higher level of compensation of the musculoskeletal system (lumbosacral spine). If the reduced flexion and extension range of motion during walking had been caused by ineffective rehabilitation, the rotation and adduction/abduction range of motion would also change, but according to our data, they remain stable. The results obtained indicate the importance of integrating the proposed dynamic gait assessment methodology into clinical practice for personalizing rehabilitation programs and early diagnosis of hidden disorders. However, limitations related to sample size require further studies including additional assessment methods (quality of life questionnaires, electromyography) in an expanded cohort of patients. Algorithms for predicting decompensation based on biomechanical markers and machine learning are to be devised to optimize treatment and improve the quality of life of patients with hip arthritis.

CONCLUSION

A rest period of at least 20 minutes between individual series of walking studies was found to be sufficient to reproduce the initial data of walking parameters and can be used in multicenter, multidisciplinary patient care. In the continuous walking group, reliable differences were obtained in the dynamics of flexion/extension in the hip joint on the intact side increasing to 35 % of the step cycle from the first to the third measurement and to 45 % of the step cycle from the first to the second measurement. No identical measurements of the manifested fatigue component were obtained in the group of patients with rest between series of passes. The analysis of continuous walking revealed the stress of the musculoskeletal compensation to achieve the optimum, while better functioning provided for the involved limb due to the greater load borne by the healthy side. The presence of the contralateral THR significantly affects the walking pattern of a patient suffering from unilateral hip arthritis: lower values of the hip flexion/extension amplitude were recorded in the presence of THR restricting excessive movements and preventing hypermobility and overload on the involved and intact sides.

Conflict of interest The authors declared no conflict of interest.

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Ethical standards. The study was conducted in accordance with the ethical standards of the Helsinki Declaration of the World Medical Association.

Informed consent. All patients participating in the study voluntarily signed informed consent for the publication of personal medical information in an anonymous form.

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