Review Paper: A Review of Selected Factors Affecting Gait Symmetry

Alireza Nasirzade[1*], Heydar Sadeghi[1], Hamid Reza Mokhtarinia[2], Abbas Rahimi[3]

1. Department of Sports Biomechanics, Faculty of Physical Education and Sport Sciences, Kharazmi University, Tehran, Iran.
2. Department of Physiotherapy, University of Social Welfare and Rehabilitation Sciences, Tehran, Iran.
3. Department of Physiotherapy, School of Rehabilitation, Shahid Beheshti University of Medical Sciences, Tehran, Iran.

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ABSTRACT

Purpose: Because walking is the main activity of humans for movement, many research studies have been conducted to understand its details. One of the main issues in this regard is gait symmetry and the effect of various factors on it. Accordingly, the present study aimed to review the selected factors affecting gait symmetry.

Methods: A literature review was performed on articles published from 2000 to 2016 using Science Direct, Google scholar, PubMed, Ovid Medline, Scopus and Medline databases. The search keywords were "gait asymmetry", "bilateral coordination", "bilateral asymmetry", "limb dominance", "laterality", "limb preference" and "performance asymmetry."

Results: A total of 60 scientific articles were selected according to the research criteria by searching the relevant articles published from 2000 to 2016 in reliable scientific databases.

Conclusion: A review of the previous studies shows that walking in normal people is asymmetric in terms of the lower limb function. Also, limb disorder due to the illness and or disorder creates gait asymmetry. Therefore, regaining perfect symmetry or decreasing gait asymmetry by exercise and intervention in such individuals is considered a method to examine the success of rehabilitation process. However, as factors like movement speed and age can affect gait asymmetry, they should be controlled during the examination of gait asymmetry. Moreover, this information could be useful for gait assessment, clinical prescriptions for patients with abnormalities, designing orthosis and prosthesis, as well as improving the performance of athletes.

1. Introduction

Gait symmetry and limbs coordination are necessary to achieve a balanced movement [1]. In biomechanical research reports, the symmetry of lower limbs is a fundamental presumption, so that the data collected, and consequently, the complexity of general data and their analysis would be significantly reduced assuming the lower limb symmetry [1]. Regardless of the research method, the pres-

*** Corresponding Author:**
Alireza Nasirzade, PhD Candidate
Address: *Department of Sports Biomechanics, Faculty of Physical Education and Sport Sciences, Kharazmi University, Tehran, Iran.*
Phone: *+98 (935) 9515557*
E-mail: *alireza.nasirzade@gmail.com*

ence or absence of gait symmetry is one of the key issues in this field, and still a matter of controversy.

From clinical perspective, asymmetry, as a pathologic factor, is an important study subject. Furthermore, gait symmetry is considered an important factor for assessing the functional inefficiency, especially in patients with different abnormalities. As a result, achieving symmetry or reducing the gait asymmetry in people with any disorder before and after rehabilitation has been used as a method for assessing the effectiveness of the therapeutic model [2 -6]. Ellis et al. [7] reported that increased gait asymmetry would increase metabolic and mechanical costs, suggesting the gait symmetry as the best prescription for healthy people. Thus, achieving full gait symmetry in most cases is an important target for physiotherapy in people with various diseases and functional anomalies [5, 8], although many other papers have not supported this claim [9, 10]. However, many scholars have discussed the issue of gait symmetry in people with and without various diseases and anomalies.

In this context, one of the issues studied by numerous papers is how the gait symmetry is affected by different factors. Meanwhile, the effect of factors such as age, gender, walking speed, as well as various anomalies and diseases, have been considered [1, 11]. However, as different methods have been used to examine gait symmetry, there is no consensus among the various articles in this regard, and some contradictory results have been presented in some cases [11]. Accordingly, as no review study has been performed to examine the effect of these factors on gait symmetry, the present review study aimed at examining the concept of gait symmetry and also the effects of various factors on it, including diseases or anomalies, movement speed, age, and gender.

2. Materials and Methods

This is a review study. Accordingly, a literature research was performed on articles published from 2000 to 2016 using Science Direct, Google scholar, PubMed, Ovid Medline, Scopus and Medline databases. The search keywords were “gait asymmetry”, “bilateral coordination”, “bilateral asymmetry”, “limb dominance”, “laterality”, “limb preference”, and “performance asymmetry” (Papers published before 2000 has been studied in the review by Sadeghi et al.) [1].

A preliminary general search resulted in about 2500 relevant articles. After reviewing the titles and abstracts, 315 articles were selected for the next stage. Finally, after reading the full texts and taking into account indicators such as simultaneous evaluation of the lower limbs’ function during the evaluation, training or rehabilitation protocols, the study of the effect of different factors on gait symmetry and indexing the article in reliable databases, 60 papers were selected as final papers for the present review study. The summary of this process is presented in Figure 1.

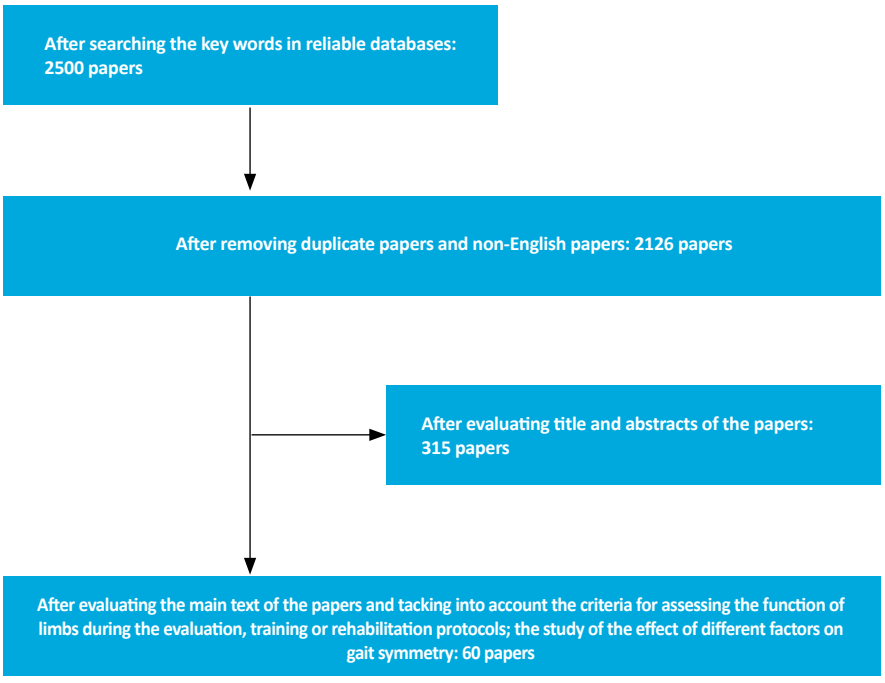


Figure 1. The process of review study

3. Results

Definition of gait symmetry

Given that numerous articles have presented different definitions and criteria for recognizing gait symmetry, a general approach should be provided. In this regard, gait symmetry is defined as a complete harmony between the activities of the lower limbs during walking [1]. However, some studies consider gait symmetry when the values measured for the lateral limbs are the same, or their differences are not statistically significant [10]. Nevertheless, despite the different definitions, the main idea for describing the concept of gait symmetry is when the bilateral limbs have similar activities [1, 9].

Gait symmetry or asymmetry

Sadeghi et al. and Nasirzadeh et al. [1, 11] prepared two review articles about the symmetry of the lower limbs during walking. Based on their studies, the performance of lower limbs in healthy people during walking at normal speed is naturally asymmetric, resulting from different functions performed by the lower limbs (Table 1). In these conditions, given that gait symmetry is the ideal state of walking for healthy people [7], the created asymmetry between the lower limbs depends on the conditions. Symmetry seems to be desirable because it facilitates control strategies. However, gait asymmetry is also needed to restore stability against internal and external disturbances [12]. Anyhow, further research is necessary to understand the main causes of gait asymmetry in healthy people.

The effect of different factors on gait symmetry

In this section, we examine four important factors affecting gait symmetry, i.e. disease and anomalies, movement speed, age, and gender.

The effect of disease and anomalies on gait symmetry

Achieving full gait symmetry is often an important target for physiotherapy in people with various diseases and functional anomalies [5, 8]. Examples of clinical trials include a comparison between dysfunctional gait and normal people with hypothetical gait symmetry [13]. A

Table 1. Studies on the lower limbs symmetry during walking (from 2000 onward)

Research Fellow	Subjects	Protocol	Variables	Results	Conclusion
Sadeghi, 2003 [9]	Healthy young men with imean(SD) age: 25.3(4.1) years	Walking at the desired speed	Muscular torque	Different functional tasks identified for joints and their similarity with the lower limbs	Local asymmetry and lower-limb symmetry of organs
Goble et al., 2003 [13]	Healthy young men with mean(SD) age: 23.8(2.2) years	Walk at three speeds (slow, normal and fast)	Ground Reaction Force (GRF)	Improvement of gait symmetry by increasing the walking speed	-
Nolan et al., 2003 [14]	Young subjects with lower limb amputation	Walking at 4 different speeds	Kinematics and vGRF	Reduced temporal asymmetry and increased vGRF asymmetry by increasing the walking speed	Asymmetry
Hesse et al., 2003 [3]	Subjects with arthroplasty of the hip joint	Walking at the desired speed	Kinematics and EMG	Further reduction in gait asymmetry after body weight support exercises on treadmill compared to conventional rehabilitation exercises	-
Perttunen et al., 2004 [15]	Teen subjects with mean age: 14.6 years with different leg length	Walking at two normal and fast speeds	GRF and plantar pressure distribution	Increased gait asymmetry at higher speeds	Asymmetry
Chockalingam et al., 2004 [16]	Teen subjects with scoliosis	Walking at normal speed	GRF	Asymmetry in GRF components between the two lower limbs and its association with scoliosis abnormality	Asymmetry
Diop et al., 2004 [6]	Healthy children aged 4-10 years old	Walking at three different speeds	Kinematics and GRF	In these people, walking was asymmetric, and it was not affected by age and speed	Asymmetry
Rodgers et al., 2004 [17]	Elderly subjects with stroke	Walking at the desired speed	Plantar pressure distribution	Reduced gait at asymmetry by increasing walking speed in these subjects	-

Research Fellow	Subjects	Protocol	Variables	Results	Conclusion
Kramers-de Quervain et al., 2004 [18]	Teen girls with unknown scoliosis	Walking at the desired speed	Kinematics and GRF	Symmetry of kinematic parameters in three dimensions, and the ground reaction force between the two lower limbs	Asymmetry
Plotnik et al., 2005 [19]	Elderly patients with Parkinson	Walking at the desired speed	Kinematics	Severe asymmetry and disharmony in lower limbs when walking	Asymmetry
Plotnik et al., 2007 [20]	Young and elderly healthy subjects and elderly patients with Parkinson	Walking at the desired speed	Kinematics	The gait asymmetry increases with age, and this asymmetry gets worse due to Parkinson	Asymmetry
Liikavainio et al., 2007 [21]	Elderly patients with osteoarthritis	Walking with normal and fast speeds	Kinematics and GRF	No asymmetry was found regarding kinematic and kinetic variables at the moment of heel contact with the ground	Symmetry
Patterson et al., 2008 [22]	Elderly patients with stroke	Walking at normal and fast speeds	Kinematics	Spatial and temporal gait asymmetry, where the temporal one was intensified by an increase in walking speed	Asymmetry
Hodt-Billington et al., 2008 [23]	Elderly subjects with and without chronic stroke	Walking with three speeds (slow, normal, and fast)	Kinematics	Except for movements of the trunk, other variables did not have the ability to distinguish between subjects, and it can be used as a factor for evaluating the patients' gait asymmetry	Asymmetry
Senden et al., 2009 [24]	Healthy men and women aged from 20 to 86 years	Walking at normal speed	Kinematics	Gender and age do not affect gait asymmetry	-
Bosch and Rosenbaum, 2010 [25]	Healthy children	Walking at normal speed	Plantar pressure distribution	At the beginning of walking, children show asymmetric behavior that decreases with aging	Asymmetry
Patterson et al., 2010 [26]	Elderly subjects with and without stroke	Walking at normal speed	Kinematics	By comparing the symmetry indices, none had superiority in the ability to differentiate, however, the symmetry ratio is recommended for the ease of interpretation	-
Seeley et al., 2010 [27]	Healthy young subjects with different lower limb lengths	Walking at normal speed	Kinematics, torque and mechanical power	The gait was asymmetrical in these individuals, and it increases by intensification of the disorder	Asymmetry
Kong et al., 2010 [28]	Healthy young subjects	Walking at normal speed	Kinematics	Physiological fatigue does not affect gait asymmetry	Asymmetry
Lythgo et al., 2010 [29]	Healthy children and young subjects	Walk at three speeds (slow, normal and fast)	Kinematics	Walking of healthy children is very symmetrical	Symmetry
Bradley et al., 2012 [30]	Elderly subjects with stroke	Walking with normal and fast speeds	Kinematics	There was a correlation between gait asymmetry and dynamic balance in these people, suggesting that an increase in their asymmetry puts them at increased risk of falling	-
Patterson et al., 2012 [4]	Elderly subjects with and without stroke	Walking at the desired speed	Kinematics	There was no relationship between gait asymmetry and age or speed for both groups	Asymmetry
Chester and Calhoun, 2012 [31]	Children with autism	Walking at normal speed	Kinematics	There is no difference between these children and healthy children in terms of symmetrical indicators and spatial-temporal parameters	-
Forczek and Staszkiewicz, 2012 [32]	Healthy young women and men	Walking at a constant speed	Kinematics	Lower limb joints during gait are asymmetrical in terms of angular changes. There was also a difference between the asymmetry of angular parameters and spatial-temporal parameters of both sexes	Asymmetry

Research Fellow	Subjects	Protocol	Variables	Results	Conclusion
La Roche et al., 2012 [33]	Healthy old women	Walking at normal speed and maximum speed	Kinematics and GRF	Gait asymmetry increases with increasing of knee extension strength asymmetry which is intensified by increasing walking speed	Asymmetry
Winiarski and Czamara, 2012 [34]	Healthy young subjects with anterior cruciate ligament (ACL) rupture	Walking at the desired speed	Kinematics	Significant improvement in asymmetry indicators of these people after 12 weeks of physiotherapy	-
Ellis et al., 2013 [7]	Healthy young subjects	Walking at a constant speed	Kinematics	Increased gait asymmetry increases the metabolic and mechanical costs , and symmetrical gait is recommended as the most optimal mode for healthy people	-
Plotnik et al., 2013 [35]	Healthy young subjects	Walking at three speeds (slow, normal, and fast)	Kinematics and GRF	There was no relationship between walking speed and its asymmetry	Asymmetry
Kobsar et al., 2014 [36]	Healthy young and elderly subjects	Walking at the desired speed	Kinematics	Gait asymmetry increases with age	Asymmetry
Kobayashi et al., 2014 [37]	Healthy young men and women	Walking at the desired speed	Kinematics	Gait asymmetry increases with age and men are more asymmetrical than women. The effect of gender on gait asymmetry was more significant than age	Asymmetry
Mahon et al., 2014 [38]	Elderly subjects with stroke - classified into two groups based on ability to walk	Walking at different speeds	Mechanical power	Mechanical power asymmetry in these people is not affected by the walking speed. It questions the prevailing thinking about walking speed as a measure of the patient's function	-
Hendrickson et al., 2014 [39]	Elderly subjects with stroke	Walking at the desired speed	Kinematics	Reduced involvement of disturbed limbs for controlling static balance is associated with spatial-temporal gait asymmetry	-

similar clinical study has been conducted on subjects with lower limb dysfunction, for example, dysfunctions caused by Parkinson disease [19, 20, 40, 41], Huntington disease [40], Autism [31], stroke [17, 22, 23, 26, 30, 38, 39], lower limb amputation [14, 42, 43], length difference [15], bone fracture [2], joint arthroplasty [3, 44, 45], osteoarthritis [5, 21], and cerebral palsy [8, 46].

Based on the present research results, the lower limb dysfunction due to disease and anomalies affects and increases the gait asymmetry (Table 1). In this case, gait asymmetry is considered an important factor to evaluate the functional inefficiency of the patients with the anomaly. Thereby, achieving gait symmetry or reducing gait asymmetry in people with any disorder before and after rehabilitation has been used to assess the effectiveness of the treatment model [2-6]. In this context, the results of several studies have also shown the effectiveness of rehabilitation exercises [3, 30, 39, 47]. However, according to different results, healthy people's gait is also somewhat asymmetric [1, 9, 10, 20, 28, 32, 33, 35, 37], that is caused by performing different functional tasks by the lower limbs [10].

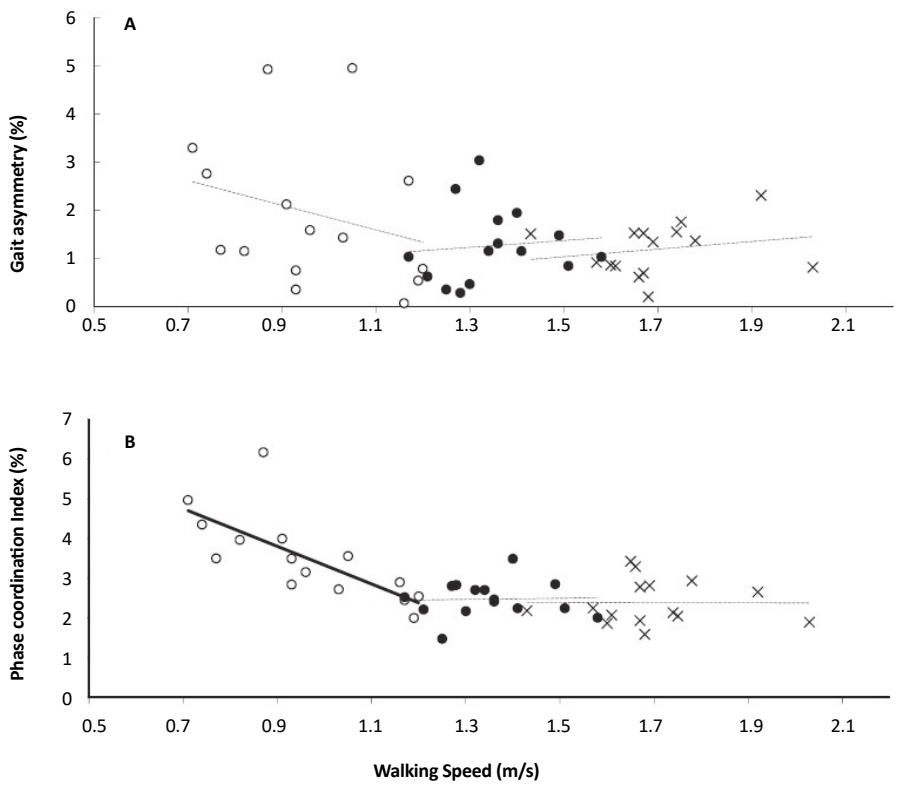
Rehabilitation clinicians need simple ways to quantify various aspects of abnormal walking to determine individual compliance with bone-articular deficiency, dysfunction, or assessment of gait changes in the elderly [48]. In this case, various instruments have been developed which provides information on automatic or semi-automatic gait asymmetry [49, 50]. The use of symmetry indices is also one of the most commonly used methods for measuring and interpreting it [11]. In this regard, several studies have compared commonly used symmetry indices and showed that none is preferred in terms of the ability to distinguish healthy subjects from people with anomaly or disease, although the symmetry ratio has been proposed because of its simplicity [4, 51].

The effect of movement speed on gait symmetry

Since changes in horizontal speed have significant and well-documented effect on the biomechanical behavior of walking [52], a reasonable assumption is also the effect of speed on the extent of gait asymmetry [13]. These conditions have been tested in patients with anomalies affecting the lower limbs, and the results have shown that decreasing or increasing the movement speed relative to the desired or normal speed affects the performance of these individuals by increasing gait asymmetry [15, 22, 33, 53].

In this case, more time is spent on the foot with abnormality (for example, the prosthetic foot) when walking at slow speed relative to the normal speed; because the entire body weight must be supported at this phase, maintaining gait symmetry is getting difficult for the person [14, 54]. With regard to the high speed of walking in patients with the anomaly in the lower limb, the people may fail to move their abnormal feet desirably [33, 39]. Under these conditions, rehabilitation exercises with emphasis on improving dysfunctional limb are recommended [33, 54]. Based on this evidence, in evaluating the gait asymmetry of elderly or subjects with any disease or anomaly in the lower limb, movement speed should be considered as a control factor, too.

However, the results of several studies on kinematic variables and GRF in healthy subjects [13, 29, 35] and people with lower limb malfunctions [17, 22, 53] showed that the increase in walking speed had no significant effect on gait asymmetry, and sometimes reduces it. Carpes et al. [55] in a review study on the reduced asymmetry in subjects when performing a task at a higher speed or power, argued that more research must be done on why gait asymmetry occurs in movements with normal speed and the kinematic symmetry occurs only in conditions with maximum effort. Hence, gait symmetry may not always be a desirable goal, and it can change according to the context of the task and subject. However, Goble et al. [13] justified this phenomenon using the theory of dynamic systems and motor control. There are various examples in this area where inter-limb coupling improves with increasing speed [56].



PHYSICAL TREATMENTS

Figure 2. Relationship between Gait Asymmetry (GA), Phase Coordination Index (PCI) and walking speed in 15 healthy individuals (7 men and 8 women with a imean(SD) age of 26.3(3.9) years). (A) For all subjects, the GA value is plotted for slow (left), normal (middle) and fast (right) walking speeds. Regression analysis showed no relationship between walking speed and GA for none of these conditions ($P \geq 0.286$, $R^2 \leq 0.09$). (B) For each subject, the PCI is presented for three walking speeds, as in the previous diagram.

Accordingly, the body segments act as pair oscillators, in which the symmetric relationships (in-phase and out-phase) are more easily maintained at higher speeds than other complex phase conditions. For example, feet are more likely to experience non-coupling and apply different functional strategies at lower speeds, while motion patterns are carried out with higher coupling and symmetry at higher speeds [13]. This finding is consistent with Plotnik et al. [35] finding, that measured GRF for gait asymmetry. Based on the results of this study (Figure 2), although no relationship was observed between three walking speeds and gate asymmetry, a significant and inverse correlation existed between walking speed and Phase Coordination Index (PCI) at low speeds, i.e. increasing PCI was inversely related to decreasing speed.

PCI is, in fact, a factor for examining a combination of precision and coordination of the walking phase, where the lower values represent a more accurate and stable walking phase, and the higher values indicate a disorder in the lateral coordination of the limbs [20]. Also, these conditions may result from sending neural signals to higher centers of the nervous system and the need for more attention at lower walking speeds [35]. Regression analysis showed only a significant linear relationship between PCI and walking at slow speed ($P=0.002$, $R^2=0.53$). Curve fitting showed that the following relationship is established between PCI and walking at slow speed:

$$PCI=B+walking\ speed\times A$$

, where A=-4.41±2.31 and B=8.8±1.20 (Dark thick line). No significant relationship was found for other speeds ($R^2<0.09$, $P>0.288$) (derived from study [35]).

The effect of age on gait symmetry

In general, aging can affect walking; for example, young people walk faster, with a longer pace, and higher stepping rates than the elderly [57]. These changes in walking may result from degradation of neurological and physical performance due to aging [37]. Since gait symmetry depends on the nervous and physical function of the individual [1], it can be expected that it decreases by aging. However, studies have reported different results. Although several studies have shown that age is not effective on gait symmetry [4, 6, 24, 48], recent studies have reported otherwise, which seems to differ in the age distribution of subjects [20, 36, 37].

Contrary to study results of nonsignificant effect over a continuous age range [4, 24, 48], some studies with significant effects [36, 37] compared two different age groups. Meanwhile, Himann et al. showed that gait function remains unchanged until the age of 60, which then varies greatly [58]. This finding justifies the report on the insignificant effect of aging on gait symmetry in subjects over a continuous age range. Because aging, especially at the age of 60 and above, can affect gait symmetry, this factor should be considered in studies along with clinical examinations. However, because it is unclear that changes in the gait symmetry occur exactly at what age, further studies in this field seem essential.

The effect of gender on gait symmetry

Like age, gender also has a significant effect on human gait parameters. Usually, women walk slower and with shorter pace than men [57, 59]. Also, previous studies have reported a significant difference between the sexes in terms of kinematic gait characteristics, including the range of motion in hip and ankle joints [60], as well as other parameters such as the mechanical energy of joints [59]. Accordingly, due to the morphological differences between two sexes, one can expect differences in the gait symmetry characteristics.

However, according to the conducted studies, the slight effect of gender on gait symmetry has not been clearly disclosed yet. Given that the gait symmetry indices used in the studies are different, several studies have reported non-significant gender effects on gait symmetry [4, 24, 48]. On the other hand, some papers have shown a significant sex-specific differences in terms of gait symmetry [32, 37]. However, drawing a definite conclusion is impossible because of few studies in this regard. In the meantime, further studies aiming at more complex variables such as joint torque during walking can provide a more comprehensive insight into the characteristics of gait symmetry and the difference between the two sexes.

4. Discussion

Based on the results of various studies, walking is an asymmetric behavior regarding the different performance of the lower limbs. Having a disease and anomaly affecting the function of the lower limbs increases this asymmetry. In this regard, achieving full symmetry after a rehabilitation period cannot be hypothetical, although its reduction is desirable. It is unclear, however, that the degree of asymmetry in the function of the lower limbs in healthy people is as high as to be considered a criterion that necessitates further research.

Also, considering the probable effect of walking speed and age on gait symmetry, it is necessary to control these

factors in future studies. Finally, such information can be useful for improving the performance of athletes, as well as for gait assessment, clinical prescriptions for patients with abnormalities, and design of orthosis and prosthesis.

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Conflict of Interest

The authors declared no conflicts of interest.

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