Symmetry function as a new tool for evaluating the symmetry of gait in transfemoral amputees

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Abstract

Background: Numerous studies have demonstrated significant asymmetries in unilateral amputee gait. The underlying dissimilarities between prosthetic and intact limbs have not yet been widely examined. To gain more insight into the functionality of asymmetries, we propose a new tool, the symmetry function (SF), to evaluate the symmetry of walking in terms of kinematic and dynamic variables of patients after unilateral transfemoral amputation and to identify areas with the largest side deviations in the movement cycle.

Methods: An instrumented motion analysis system was used to register the gait of fourteen patients after unilateral trans-femoral amputation (TFA). Measurements involved evaluating the time series of gait variables characterizing a range of motion and the time series of the ground reaction force components. Comparison of the involved limb with the uninvolved limb in TFA patients was carried out on the basis of the SF values.

Results: The symmetry function proved to be an excellent tool to localize the regions of asymmetry and their positive or negative directions in the full gait cycle. The difference between sides revealed by the symmetry function was the highest for the pelvis and the hip. In the sagittal plane, the pelvis was asymmetrically tilted, reaching the highest SF value of more than 25% at 60% cycle time. In the transverse plane, the pelvis was even more asymmetrically positioned throughout the entire gait cycle (50% difference on average). The hip in the frontal plane reached a 60% difference in SF throughout the single support phase for the prosthetic and then for the intact limb.

Conclusions: The symmetry function allows for the detection of gait asymmetries and shifts in the center of gravity and may assess the precise in time adaptation of prostheses and rehabilitation monitoring, especially in unilateral impairments.

Trial registration: The trial registration number (TRN): 379991 issued by the Australian New Zealand Clinical Trials Registry (ANZCTR) on 07.05.2020 (retrospectively registered).

1. Introduction

Assessment of gait symmetry is one of the main criteria for assessing the process of improving patients with various musculoskeletal disorders. In the case of patients after transfemoral amputation (TFA), gait parameters are evaluated by referring the obtained amputated data either to the whole limb or to the data of healthy people. Walking patterns in healthy people concerning time, distance, and vertical force are quite symmetrical, deviating in only a small percentage from ideal symmetry [1]. For example, the difference between the two lower limbs calculated using the symmetry index [2] for time measures and vertical force is less than 6% for normal gait [3–5]. In a pathological gait, however, an asymmetry between the lower limbs can be noticeably observed. Shorter support phase, extended swing time and reduced ground reaction forces (GRF) have been reported on the affected limb in the gait of people with hemiparesis or osteoarthritis and in persons with prosthetic limbs [6–11].

One of the leading causes of gait asymmetry in people after TFA is a disturbance of the coordination of muscles acting on the hip joint resulting from the removal of femoral ends of muscles, such as hamstrings, adductors, rectus femoris and sartorius. This reduces the ranges of motion for both flexion and extension in the hip joint. Conversely, the iliopsoas and gluteus maximus and medius muscles have not been shortened and act in the hip joint as agonist muscles with less antagonistic muscle activity [12]. Transfemoral amputees adopt compensatory strategies during walking. Vahidrez and coworkers indicated the significant role of hip extensors in compensating for the reduced flexors of this joint after amputation while walking. The gluteus maximus contributed more to propulsion and support, while the gluteus medius contributed more to balance than other muscles in the intact limb than the residual limb [13]. Research shows many factors are affecting the asymmetry of gait in patients after TFA. Apart from the cause of amputation and the time that elapses from the subtraction of the limb, the most important one is the length of the stump and the type of prosthesis [14,15]. The most common complication after TFA is limp gait, expressed by reducing the time of single support [16,17]. Walking tests using various funnels were carried out by Rabuffetti et al. [18]. They assessed the degree of asymmetry of the flexion and extension of the hip joint and the angle of the pelvis (*pelvic tilt excursion*) in patients equipped with different types of orthoses. Many researchers point to the fact that the use of microprocessor modules significantly affects the quality of gait, which is manifested by a lesser amount of asymmetry of gait between the limbs [14,15,19,20]. Another factor affecting the degree of asymmetry of gait is the speed of walking. The increase in gait speed results in a smaller range of

hip flexion, which in turn leads to shortening of the step length of both limbs in the walking cycle, while the length of the step of the amputated leg is significantly shortened [21,22]. An essential factor improving the patient's quality of gait is to progress the activities of a physiotherapist or through activity in the sport of people with disabilities. Hence, researchers' interests are focused on assessing the degree of asymmetry of muscle strength, acting on the hip joint [20,23,24]. It is also indicated that sports training, which enhances muscle strength, may be an effective form of patient therapy. However, a patient needs to undergo evaluation of their muscle strength and have the therapy program adjusted to their level of muscle strength deficit. Studies of patients after TFA actively participating in various Paralympic sports show that there is a statistically significant relationship between gait asymmetry and the strength of the hip extensors muscles [25].

In many publications, gait assessment of patients after TFA is based on a comparison of the components of the ground reaction forces: vertical, anteroposterior and lateral [25–30]. Scientific research shows that especially the asymmetry of the vertical component of the ground reaction force between the limbs can, as a result of long-term asymmetry, lead to degenerative changes within all joints of the healthy lower limb. Particularly prone to degeneration is the knee joint, in which the range of motion is limited first (mainly during extension), which then leads to arthrosis. This is because patients protecting the amputated limb transfer their weight to the unoperated limb [13,26,27]. Asymmetry of the amputee's gait is manifested at various times during the gait phases and in particular during the support phase. Another manifestation of the asymmetry of the gait of people after TFA is shorter stance (60%) on the prosthetic side and a wider stride (4 cm) when compared to controls [26].

Different formulas were previously adopted to evaluate side differences in an impaired gait, such as symmetry ratio [31], symmetry index [20,32], asymmetry index [16], ratio index [21], logarithmic transformation of the ratio [33], and factor asymmetry [34]. Although commonly used scalar indicators are an effective measure of temporal and spatial asymmetry, they still do not provide a comprehensive assessment of gait symmetry. This was demonstrated, among others, by Roerdink et al. [35], who noticed that step length asymmetry for amputated people (measured using the symmetry index) differed between participants and that some of them showed symmetry even though their gait was asymmetrical. Therefore, a single measure cannot provide comprehensive information about gait symmetry because the asymmetries in the angle-time characteristics from which these metrics are derived are not well characterized by discrete values. To accurately assess the symmetry of gait, the entire limb should be considered throughout the gait cycle [5]. This suggests the need for more complex mathematical methods for measuring symmetry [36]. One such tool may be the dynamic symmetry function (SF), which was proposed to evaluate side deviations in human gait [37,38], but so far, it has not been used in the analysis of the locomotion of people after unilateral TFA. Therefore, the current work aims to evaluate the symmetry of walking in terms of kinematic and dynamic variables of people after unilateral TFA and to identify areas with the largest side deviations in the movement cycle. The main research question asked the following: *Whether the symmetry function is a valuable tool to localize the regions of symmetry and asymmetry in the whole cycle of the gait of subjects after TFA*.

2. Material And Methods

Participant characteristics

Fourteen participants (mean age 46 ± 14 years, body height 1.76 ± 0.09 m and weight 79.6. ± 18.3 kg) after unilateral trans-femoral amputation (TFA) participated in the study. Some of the subjects actively engaged in sports activities, such as wheelchair tennis, sitting volleyball, swimming and bodybuilding. The characteristics of the subjects taking into account orthopedic supplies are presented in Table 1. All subjects used the prosthesis daily (for a minimum of six months before the study) and did not use any other walking support devices. The exclusion criteria to the study were: pain in the area of the stump or lower limb and chronic diseases that could have a direct impact on the efficiency of the musculoskeletal system.

Before the start of the study, all participants were informed about the purpose of the study and the possibility of withdrawing participation at any stage, without giving a reason, following accepted ethical standards and provided informed consent. All procedures performed in this study were in accordance with the ethical standards of the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. The research project received a positive opinion from the Wroclaw Medical University's Ethics Committee (Ethics approval No KB–232/2016).

Table 1. Characteristics of the subjects, taking into account height, weight, age, cause and side of amputation as well as the characteristics of orthopedic supplies.

No	Body height [m]	Body mass [kg]	Age [y]	Cause	Side	Stump length [cm]	Socket type	Prosthetic KNEE	Prosthetic FOOT	Sport activity
S1	1.71	73.2	46	Trauma	R	29.5	ICS Anatomica	C-Leg®	1C40 C-Walk®	Body building
S2	2.00	106.0	43	Trauma	L	35.0	ICS Anatomica	C-Leg®	1C40 C-Walk®	_
S3	1.78	96.0	63	Trauma	L	29.0	Marlo Anatomical Socket (MAS®)	3R80®	1C30 Trias®	_
S4	1.83	111.5	19	Congenital Malformation	L	34.0	ICS Anatomica	3R95®	1C30 Trias®	
S5	1.82	93.0	45	Trauma	R	21.0	ICS Anatomica	C-Leg®	1C40 C-Walk®	
S6	1.71	58.3	20	Cancer	R	22.0	ICS Anatomica	C-Leg®	1C40 C-Walk®	Swimming
S7	1.75	81.0	54	Trauma	L	24.0	ICS Anatomica	3R80®	1C30 Trias®	Volleyball
S8	1.68	60.0	36	Vascular	L	27.0	ICS Anatomica	3R80®	1C30 Trias®	_
S9	1.64	46.4	21	Cancer	L	22.5	ICS Anatomica	C-Leg®	1C60 Triton	Swimming
S10	1.70	80.2	33	Congenital Malformation	L	24.0	ICS Anatomica	3R95®	1C30 Trias®	_
S11	1.70	58.1	64	Cancer	R	25.5	Marlo Anatomical Socket (MAS®)	3R80®	1E56 Axtion®	_
S12	1.83	97.0	58	Trauma	L	32.0	ICS Anatomica	C-Leg®	1C60 Triton®	Tennis
S13	1.63	59.7	38	Trauma	R	28.5	ICS Anatomica	C-Leg®	1C60 Triton®	_
P14	1.81	93.6	41	Cancer	R	25.0	ICS Anatomica	C-Leg®	1C40 C-Walk®	Volleyball

Experimental protocol and setup

The study was carried out in the certified Laboratory of Biomechanical Analysis (PN-EN ISO 9001:2001) by the BTS Smart-E system (BTS Bioengineering, Milan, Italy), which utilizes six infrared digital cameras (1.1 μm infrared light, 120 fps in 768 x 576 px resolution), two Network Cam AXIS 210A cameras operating within visible range at a frequency of 20 Hz and two piezoelectric force plates type 9286A (Kistler Instrumente AG, Winterthur) designed specifically for use in gait analyses with a measurement threshold of more than 250 mN and a range of 0-5 kN for the vertical component. Data were collected by digital USB/PC input and processed in a BTS Smart Analyser program. A total of 22 photoreflective markers were placed on the subject's body, following the standard procedure for the Davis model.

Measurements involved evaluation of a time series of gait variables characterizing motion of the pelvis and the main lower extremity joints, such as:

- pelvic obliquity (POBLI): upward or downward movement of the pelvis (with respect to a global coordinate system) in the frontal plane due to rotation of the mediolateral axis out of the horizontal plane;
- pelvic tilt (PTILT): anterior or posterior movement of the pelvis in the sagittal plane due to rotation around the mediolateral axis;
- pelvic rotation (PROT): internal or external movement of the pelvis in the transversal plane due to rotation of the mediolateral axis about the vertical axis;
- hip ad/abduction (HPAA): movement of the femur with respect to the pelvis coordinate system in the frontal plane due to rotation of the proximal-distal axis out of the sagittal plane;
- hip flexion-extension (HPFE): movement in the sagittal plane due to rotation of the proximal-distal axis about the mediolateral axis;
- hip rotation (HPROT): internal or external movement in the transversal plane due to rotation around the proximal-distal axis;
- knee flexion-extension (KFE): movement of the tibia with respect to the femur coordinate system in the sagittal plane due to rotation of the proximal-distal axis about the mediolateral axis;
- ankle flexion-extension (AFE): movement of the foot with respect to the tibia coordinate system in the sagittal plane

and three ground reaction force (GRF) orthogonal components: vertical (vGRF), anterior-posterior (a-pGRF) and mediolateral (m-lGRF) as a function of normalized time (% of stance time, %ST or cycle time, %CT). The GRF components were normalized to body weight and expressed in percentages (%BW). The GRF data were collected with the frequency of 1 kHz and with the use of two force plates situated at the center of a walking pathway. Measurement of the GRF was synchronized and controlled by the motion analysis system. A 6-m walking distance at a self-selected speed enabled the recording of 3 to 4 complete gait cycles. Each walking trial was repeated and recorded four times, which allowed us to collect from 12 to 16 gait cycles per subject.

Data analysis

To investigate the symmetry, we used dynamic symmetry function (SF), which is a function of time and expresses the percentage difference between the involved $X_{IN}(t)$ and uninvolved $X_{UN}(t)$ sides relative to an average range of change.

$$SF(t) = 2 \cdot \frac{x_{in}(t) - x_{un}(t)}{Range(x_{in}(t)) + Range(x_{un}(t))} \qquad (1)$$

The symmetry function can be interpreted in a similar way as the symmetry index, with values of SF less than approx. 5% indicating good symmetry, values from 5-10% indicating moderate symmetry and values above 10% indicating asymmetry. Positive values indicate an advantage (higher value) of the involved side over the uninvolved one [38].

For each participant and each of the measured cycles, time normalization of the right and left angles for the sagittal plane or GRF components was performed numerically, utilizing decomposition of a time series (trend detection) using the Lagrange interpolation polynomial (MATLAB script). In this way, right and left cycles of the same length (100%CT for angles and 100%ST for GRF components) with discrete values (every 0.5%) were obtained. The graphs of the range of motion in joints and SF function were parameterized to compare values between groups. For each graph, separately for the left and right side, the highest and lowest values reached by the assigned angle-time characteristics during a test were extracted, including peak maximum ($Peak_{max}$) and peak minimum ($Peak_{min}$) values, range of changes in ROM in degrees [º], and time to reach peak values t_{min} and t_{max} in percent of the time of gait cycle [%CT].

Statistical analyses

In addition to graphical results, the analysis of the distribution of all variables was assessed by the Shapiro-Wilk test. The basic descriptive statistics (arithmetic means and standard deviations) were evaluated for the extracted values of $Peak_{min}$, t_{min}, $Peak_{max}$, t_{max} and ROM. The nonparametric U Mann-Whitney test was used to test the differences between sides and between events for different profiles of angles and SF function (a=0.05). All statistical analyses were performed in Statistica 13.1 (TIBCO Software Inc).

3. Results

The graphs show the differences between the sides (side variations) in terms of movements in the joints of the lower limbs (Figure 1) and the corresponding symmetry function (SF) (Figure 2) in the TFA group. A positive sign of SF means that the involved limb obtained a greater angle value than the uninvolved limb in the study. Table 2 summarizes the most important differences between the sides in the parameters of angular functions and symmetry, detailing their statistical significance.

The pelvis in the frontal plane was symmetrical during the initiation of the step (at foot contact). The biggest differences between the sides in pelvic obliquity were recorded in midstance (approximately 25 percent of cycle time (%CT)) and at initial- and mid-swing, where SF values reached 15-20% values. These differences for the $Peak_{min}$ were statistically significant (Table 2). The positioning of the pelvis in the sagittal plane (pelvic tilt) at the beginning of step initiation (at initial contact) was not symmetrical. The SF value reached a value of 20%. Then, in the middle stance, movement was symmetrical, and after a while in terminal stance, it became again asymmetrical. The highest SF value was 25.4% at 59 %CT (Table 2). The end tail of pelvic tilt also turned out to be asymmetrical, where the SF value reached the lowest value (-21.9%). However, there were no statistically significant differences between the peak values ($Peak_{min}$ and $Peak_{max}$) and in the case of the range of motion (ROM) (Table 2). In the transverse plane, the pelvis was asymmetrically positioned and tilted towards the limb throughout the entire gait cycle. The size of the asymmetry oscillated approximately 50% throughout the movement, and the differences in the peak values were statistically significant. Movements in the hip joint largely reflected pelvic movements. In the frontal plane, the involved limb had a smaller range of motion than the uninvolved limb, and the differences in SF reached up to 60% from the initial double support phase to mid-swing. The differences in peak values were also statistically significant. Movements in the sagittal plane were generally symmetrical (SF 7.7% and less), and no statistically significant differences were found between the peak values. One of the biggest differences between the involved and uninvolved sides occurred in the transversal plane. Throughout the gait, the involved limb had significantly higher angle values than the uninvolved limb, and the symmetry function value oscillated from the value of 26.1 ± 2.31% at 56 %CT to 57.9 ± 2.89% at 94 %CT. All the differences in the peak values were statistically significant.

Movements in the other analyzed joints were repeatable between the sides. The knee flexion-extension angle did not differ by more than 4% throughout the entire walking task, and the ankle plantar-dorsiflexion angle reached the value of -19.2% only during the swing phase. There were also no statistically significant differences between the peak values.

The times of the occurrence (timing) of extreme values (Peak minimum and maximum) most often did not coincide with the times of the occurrence of the extreme values of symmetry functions (Table 2). The only agreement was observed in pelvic movements for the time of maximum value (t_{max} for $Peak_{max}$) in the pelvic tilt. The other $Peak_{min}$ and $Peak_{max}$ values for all other analyzed movements turned out to be significantly different.

*** FIGURE 1 HERE ***

Figure 1. Range of motion in main low extremity joints characterizing pelvic obliquity (POBLI), pelvic tilt (PTILT), pelvic internal/external rotation (PROT), hip ad/abduction (HPAA), hip flexion-extension (HPFE), hip rotation (HPROT), knee flexion-extension (KFE) and ankle flexion-extension (AFE). The curves represent how a single, angular variable varies over the gait cycle (expressed in %). The dark line represents the involved side, and the dashed red line represents the uninvolved side.

*** FIGURE 2 HERE ***

Figure 2. Symmetry function curves for main lower extremity joints characterizing symmetry of pelvic obliquity (POBLI), pelvic tilt (PTILT), pelvic internal/external rotation (PROT), hip ad/abduction (HPAA), hip flexion-extension (HPFE), hip rotation (HPROT),

knee flexion-extension (KFE) and ankle flexion-extension (AFE) as a function of normalized cycle time. The function represents the side difference in relation to its averaged range of change.

Table 2. Mean and ± standard deviation for the parameters characterizing range of motion and the corresponding symmetry function.

	Angle [º]		Symmetry
	Involved	Uninvolved	Function [%]
Pelvic obliquity (POBLI)			
$Peak_{min}$	-3.9*±2.05	-5.9±2.15	-2.7±1.09
t_{MIN} [%CT]	35.0#±1.74	34.0#±2.20	55.0±1.49
$Peak_{max}$	5.8±2.11	3.3±2.08	20.4±2.14
t_{MAX} [%CT]	84.0#±1.34	86.0#±3.61	72.0±2.22
ROM	9.7±2.36	9.2±2.45	23.1±1.55
Pelvic tilt (PTILT)			
$Peak_{min}$	12.5±2.10	12.6±2.00	-21.9±1.98
t_{MIN} [%CT]	79.0*,#±1.58	31.0#±0.50	88.0±1.14
$Peak_{max}$	18.2±2.02	18.4±2.62	25.4±1.79
t_{MAX} [%CT]	52.0*±0.68	2.0#±0.57	59.0±2.71
ROM	5.7±2.25	5.7±2.08	47.3±1.28
Pelvic rotation (PROT)			
$Peak_{min}$	-2.1*±2.05	-5.9±2.22	37.9±1.57
t_{MIN} [%CT]	63.0±1.45	61.0#±2.87	67.0±2.41
$Peak_{max}$	6.7*±2.00	1.9±2.05	53.9±2.00
t_{MAX} [%CT]	6.0*,#±1.20	7.0#±1.23	2.0±0.04
ROM	8.8*±2.23	7.8±2.05	16.0±1.42
Hip ad/abduction (HPAA)			
$Peak_{min}$	-9.8*±2.38	-4.3±2.05	19.0±1.53
t_{MIN} [%CT]	68.0#±1.27	65.0#±2.41	0.1±1.00
$Peak_{max}$	-2.7*±2.04	0.3±2.01	59.8±1.91
t_{MAX} [%CT]	0.2*,#±1.30	90.0#±2.70	70.0±1.68
ROM	7.2*±2.08	4.6±2.13	40.9±1.63
Hip flexion-extension (HPFE)			
$Peak_{min}$	-2.3±2.08	-1.7±2.02	-7.7±1.02
t_{MIN} [%CT]	56.0#±2.35	56.0#±1.12	4.0±0.19
$Peak_{max}$	37.7±2.57	34.5±2.38	6.2±1.12
t_{MAX} [%CT]	0.1*,#±0.45	97.0#±1.85	43.0±1.11
ROM	40.0±2.20	37.2±1.65	13.9±1.36
Hip rotation (HPROT)			

$Peak_{min}$	-1.2*±2.05	-7.8±2.06	-57.9±2.84
t_{MIN} [%CT]	13.0*,#±1.14	22.0#±0.86	94.0±1.60
$Peak_{max}$	6.4*±2.18	0.3±2.00	-26.1±2.31
t_{MAX} [%CT]	87.0*,#±1.35	57.0±1.43	56.0±1.50
ROM	7.5*±2.31	8.1±2.35	31.8±1.46
Knee flexion-extension (KFE))			
$Peak_{min}$	0.4±1.01	-0.5±1.09	-1.8±0.60
t_{MIN} [%CT]	0.1#±0.50	0.2#±0.30	97.0±1.37
$Peak_{max}$	47.2±1.89	47.4±1.71	3.8±0.91
t_{MAX} [%CT]	76.0#±3.80	76.0#±1.60	71.0±2.06
ROM	46.8±1.87	47.9±2.57	5.7±1.02
Ankle flexion-extension (AFE)			
$Peak_{min}$	-10.5±2.40	-12.8±2.55	-19.2±1.17
t_{MIN} [%CT]	72.0#±2.02	71.0#±2.27	64.0±2.38
$Peak_{max}$	6.0*±1.05	5.4±1.15	1.3±1.04
t_{MAX} [%CT]	51.0#±2.19	50.0#±2.10	5.0±2.02
ROM	16.4*±1.49	18.2±1.66	20.5±1.41

** significant difference between sides, a<0.05, # significant difference between time events for angles and SF, a<0.05*

Figure 3 shows the differences between the sides (side variations) in the components of the ground reaction force and the corresponding symmetry function (SF) in the group of patients after uTFA. A positive sign of SF indicates that in the study, the involved limb obtained greater angle values than the uninvolved limb. In addition, Table 3 summarizes the most important differences between the sides in the parameters of the components of the ground reaction strength, specifying their statistical significance.

All components of the ground reaction force showed differences between the involved and the uninvolved sides in patients' gait, as revealed by the SF function. The absolute difference between the maximum value (Max) and the range of change (Range) for the vertical component of GRF was 3.2 percent of body weight (%BW) and was significantly different ($p < 0.05$), with the value of symmetry not exceeding 5% in the area. The mean value of symmetry function in the entire anteroposterior range was -1.0 ± 1.1% and oscillated from the smallest value (Min) of approximately -7% at the beginning (at approximately 10%ST) and at the end of the support phase (at approximately 85 % ST) and the highest value (Max) of approximately + 7% in the middle support (at 60 %ST). These areas are marked in red in Figure 3. At the same time, the differences in the Min and Max extreme values between the involved and uninvolved sides were not statistically significant. The mediolateral GRF component was characterized by the largest asymmetry, and the areas with the largest differences occurred at the beginning of the support (between 10 and 40%ST) and in the propulsive phase at the end of the support (between 80-90%ST). The average value of symmetry function throughout the entire cycle of movement was 0.4 ± 1.3% and varied from the smallest value (Min) of approximately -9% to approximately 12% (Max). Similarly, differences in the Min and Max extreme values between the involved and uninvolved sides were not statistically significant.

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*** FIGURE 3 HERE ***

Figure 3. Side deviations of the main components of ground reaction function: vertical, anteroposterior and mediolateral for the involved (dashed red line) and uninvolved sides (dashed blue line) with corresponding symmetry function (solid dark line). The curves represent how a single variable varies over the gait cycle (expressed in %). Areas exceeding +/- 5% symmetry threshold are marked in red

Table 3. Mean and ± standard deviation for the parameters characterizing vertical, anteroposterior and mediolateral components of ground reaction force together with the corresponding symmetry function (SF). The normalized force was expressed as a percentage of body weight [%BW], symmetry function as a percentage [%] of a side, average range of change in the force components, according to Eq.1.

	Vertical GRF [%BW]			Anteroposterior GRF [%BW]			Mediolateral GRF [%BW]		
	Inv	Uninv	SF [%]	Inv	Uninv	SF [%]	Inv	Uninv	SF [%]
mean±SD	71.8±7.4	72.4±7.6	3.7±0.6	0.1±1.9	-0.2±2	-1.0±1.1	4.2±0.6	4.3±0.7	0.4±1.3
Min	0	0	4.8±0.6	-10.8±0.2	-12.3±0.2	-7.1±0.1	-1.2±0.1	-1.2±0.1	-8.9±0.1
Max	96.0*±1.3	99.2±2.1	4.9±0.6	14.0±1.9	13.4±2.0	6.9±1.1	7.0±0.6	6.9±0.7	11.9±1.3
Range	96.0*±1.3	99.2±2.1	9.7±0.7	24.8±1.7	25.7±1.9	6.9±1.0	8.1±0.7	8.0±0.6	20.8±1.2

* *significant difference between sides, a<0.05*

4. Discussion

To accurately assess the symmetry of motion, the side differences should be assessed throughout the entire movement cycle [33]. Such a method may be the dynamic symmetry function (SF), based on commonly used symmetry index [2], which was previously used to assess the gait of patients after unilateral total hip replacement [28]. The symmetry index is a standard measure of asymmetry and quality of walking and can be seen as an essential topic in gait analysis. In particular, it increases the energy cost of walking and agrees with the dynamic balance deficits. The asymmetry can affect all aspects of gait, for example, spatially, by unequal step lengths between right and left, or temporally, by dissimilarity in time spent in the stance or swing phase between the two feet [26], and finally, by inequality in the joint kinematic characteristics and ground reaction forces [11,16].

Many authors point out that asymmetric gait patterns and the resulting increase in hip joints of transfemoral amputees may be associated with a higher risk of lower back pain (LBP) and hip osteoarthritis of the intact limb [33,39]. Reducing gait asymmetry through effective rehabilitation reduces the degree of stutter and, consequently, reduces the possibility of faster occurrence of degenerative changes in the contralateral knee joint and a decrease in the incidence of the LBP. The registered mechanism of changes in the range of motion of the pelvis and hip joint is an expression of compensatory movements aimed at alignment of the asymmetrical gait pattern. Investigations show that transfemoral amputation is not always the cause of the LBP. Morgen and coauthors [40] analyzed the kinematics of gait in TFA people with and without LBP. Transfemoral amputees with LBP showed higher transverse plane rotation in their lumbar spine during walking compared to amputees without LBP. The reason may be associated with intervertebral disc degeneration, suggesting that increased transverse plane rotation, secondary to walking with a prosthetic limb, may be a factor in the etiology of low-back pain in transfemoral amputees [40]. Risk of LBP events appears to vary by TFA etiology. Obesity did not correlate significantly with increased frequency of LBP events or time to the events. Phantom limb pain correlated with decreased time to LBP events after amputation. The association between prosthesis receipt and LBP events is ambiguous [41].

Moreover, prolonged time asymmetric loading of the lower limb may result in atrophy of stump muscles and degenerative changes in the joints [25]. The main challenge is to choose the adequate calculation of asymmetry depending on what aspect of gait one wants to assess. Usually, the easiest way is to calculate the difference between two sides, either with raw or absolute values, with or without reference to the average range. Different formulas were adopted, such as symmetry ratio, symmetry index, logarithmic

transformation of the ratio or angle of symmetry [16,20,31–33], to objectively quantify the assessed phenomenon. These mathematical methods have been utilized in various clinical applications with different diagnostic values in relation to kinematic data [42]. Each approach demonstrated a similar advantage in terms of discriminative ability and has some significant disadvantages or shortcomings. The index is a single value which strongly depends on selected data points and reference values [42].

The symmetry analysis in our study assessed differences in the whole measured range and very accurately specified the areas where the symmetry was the largest or the smallest. Moreover, a symmetry function (SF) close to zero represented perfect symmetry, and the positive/negative sign indicated the direction of the asymmetry, while the value indicates the magnitude of asymmetry. The SF not only estimated symmetry values in the region of maximum value occurrence for which symmetry is most often assessed but also checked the proximity of these areas. The SF designated sections that were similar or not and indicated their degree of differentiation (difference?). The method is precise (for both large and small values) objective and standardized. Its values represent the degrees of similarity (symmetry) or difference (asymmetry) of the compared graphs. The correspondence with the scalar values is also confirmed by the statistical analysis between the peak values for the extracted parameters of time courses of articular angles. It is better to use tools already established and well known as the formulas for symmetry functions to compare successive evaluations or several subjects.

In the present study, gait of patients after unilateral TFA was characterized by an asymmetric range of motion in the main body joints. The pelvis and hip movements had the highest SF value, which was confirmed by statistical tests and the largest asymmetric areas revealed by the function. The most significant differences in pelvic obliquity were recorded during midstance (approximately 25 percent of cycle time (%CT)) and at initial- and mid-swing, where SF values reached more than 20%. In the sagittal plane, the pelvis tilted asymmetrically at the beginning of step initiation. The SF value reached more than 20%. Subsequently, in middle stance, movement was symmetrical, and in terminal stance, movement was again asymmetrical. The highest SF value was more than 25% at 60 %CT. In the transverse plane, the pelvis was even more asymmetrically positioned throughout the entire gait cycle. The size of the asymmetry was approximately 50% throughout the whole movement. Movements in the hip joint essentially mirrored the movements of the pelvis. The differences between the involved and uninvolved sides in topmost values were also statistically significant. In the frontal plane, the differences in SF reached 60% throughout the first part of the cycle. Movements in the sagittal plane were mostly symmetrical. Nevertheless, one of the most significant differences occurred in the transversal plane. Throughout the gait, the involved limb had significantly higher angle values than the uninvolved, and the symmetry function value oscillated from approximately 25% to 60% throughout the swing phase. Movements in the other studied joints had a repeatable pattern, e.g., the knee flexion-extension angle did not differ by more than 4% throughout the entire walking task, and the ankle plantar-dorsiflexion angle reached the value of -19.2% only during the swing phase. Similarly, no statistically significant differences between the peak values were present.

The asymmetry of the hip (resulting directly from a reduction of the hip angle at foot strike during the contact phase) may result from keeping the knee prosthesis straight at the beginning of the support phase [22]. However, the symmetry varied depending on the socket type and gait speed – the stability of interlimb coordination increases with walking velocity, and the prosthesis-induced asymmetry diminishes at higher walking velocities [21]. Moreover, the pelvis is significantly more anterior tilted at foot strike for the uninvolved limb. The increased pelvic tilt in sync with hip flexion for the uninvolved side is a compensating strategy adopted to obtain a functional step length and symmetrical thigh inclinations [18]. For the intact, uninvolved limb, hip range of motion in the sagittal and frontal planes turned out to be significantly larger than for the residual, prosthetic limb [13], which demonstrated the role of the intact limb in compensating for reduced or absent muscles and joint function in the residual limb of TFA patients during walking.

The timing of extreme values (minimum and maximum) for the range of motion most often did not coincide with the time of occurrence of the extreme values of the SF function. The single agreement was observed in pelvic movements for the time of maximum value in tilting the pelvis. The timing of events for other analyzed movements was significantly different.

The maximum value of the vertical ground reaction force (GRF) component assessed throughout the entire gait cycle was usually the highest in the supporting phase of the TFA gait pattern, and its value for the amputated limb was significantly lower than that for the uninvolved limb [29,43,44]. Our previous research showed that variables describing GRF behavior were statistically smaller

for the amputated limb regarding values for healthy controls by almost 7.7 percent of body weight (%BW) in the supporting phase, 12.3 %BW in terminal stance, and 12.0 %BW for the posterior braking force at initial stance [25]. Values of the vertical component of GRF during underweight in middle stance were on average 5.8 %BW higher for the amputated limb. In our study, all the components of the ground reaction force (GRF) showed a difference between sides, as revealed by the SF function. The value of symmetry seldom exceeded 5% in the supporting area. The involved limb was characterized by less value of reaction force in the weight acceptance phase, especially between 5-40 percent of the stance time (%ST). The mean value of symmetry function in the entire anteroposterior range was -1.0 ± 1.1% and oscillated from the smallest value (Min) of approximately -7% at the beginning (at approximately 10 %ST) and at the end of the support phase (at approximately 85 %ST) and the highest value (Max) of approximately 7% in the middle support (at 60 %ST). These areas are marked in red in Figure 3. At the same time, the differences in the Min and Max extreme values between the involved and uninvolved sides were not statistically significant. The mediolateral GRF component was characterized by the largest asymmetry, and the areas with the largest differences occurred at the beginning of the support (between 10 and 40 %ST) and in the propulsive phase at the end of the support (between 80-90 %ST). The average value of symmetry function throughout the entire cycle of movement was 0.4 ± 1.3% and varied from the smallest value (Min) of approximately -9% to 12% (Max). Similarly, differences in the Min and Max extreme values between the involved and uninvolved sides were not statistically significant.

The dynamic symmetry function proved to be a good tool to localize the regions of asymmetry and their positive or negative direction in the full gait cycle of transfemoral amputee gait. In the study group, there were differences in anteroposterior GRF forces between limbs, expressed as a change in their value. The amputated limb carried a higher load than the healthy limb. In addition, areas of increased pelvic and hip joint asymmetry were registered in the study group, mainly in the transverse and frontal planes. For this reason, there is a justified risk of bearing a higher load on the thigh stump of the amputated limb inside the socket. This is due to the lower protection of the amputated stump in the funnel for rotational movements (in the transverse plane) than for flexion-extension movements (in the sagittal plane). In rehabilitating people after TFA, overturning the maximum possible gait function determines the patient's future quality of life. Thus far, the use of the results of comprehensive movement analysis and their results in the daily practice of the rehabilitation team has been limited, influenced by the need to have appropriate training to interpret the results and to provide time for their analysis. In addition, the conclusions of the analysis were challenging to apply in daily therapy. By using the SF symmetry measure, data analysis is more accessible by detecting areas of asymmetry. The ability to interpret and use the results obtained is easier, which, in turn, enables more precise development of therapy goals. Imaging of asymmetry areas, in addition to information for the rehabilitation team, has additional functions for the person after TFA subject to improvement on the basis of feedback: the ability to assess the progress of improvement, by both the team and the patient, positively affects the active participation of the patient in rehabilitation.

Conclusions

- It is better to use parameters already established and standardized to assess symmetry, compare the results of successive evaluations or several subjects.
- The SF distinguishes areas of highest or lowest asymmetry and provides information on the symmetry of movement in the entire range of motion, in contrast to symmetry indices which are calculated for selected parameters and events.
- The symmetry function allows for detection of gait asymmetries and shifts in the center of gravity and assesses the precise adaptation of prostheses and rehabilitation monitoring, especially in unilateral impairments.
- Pelvic and hip movements are of the highest value of symmetry function in unilateral TFA gait.
- The time of occurrence of extreme values (minimum and maximum) of the range of motion most often does not coincide with the time of occurrence of the extreme values of symmetry function.

Study Limitations

The present study has some potential limitations. The research was carried out in the clinical conditions of only one medical center. The size of the TFA group was not significant and was not sufficiently representative to generalize changes in registered reaction forces and ranges of motion to the whole population of patients who have experienced unilateral above-the-knee amputations.

Declarations

Ethics approval and consent to participate

All participants provided informed consent. The procedures complied with the Declaration of Helsinki regarding human experimentation. The research project received a positive opinion from the Wroclaw Medical University's Ethics Committee (Ethics approval No KB–232/2016).

Consent for publication

Not applicable.

Availability of data and materials

The data collected during this study will be provided upon request made to the corresponding author.

Competing interests

The authors declare that they have no competing interests.

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Authors’ contributions

SW and MK conceived the study. SW performed data and statistical analysis. SW, MK and ARK contributed to study design and data collection, writing of the manuscript. SW, MK and ARK also revised and approved the final manuscript.

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Figures

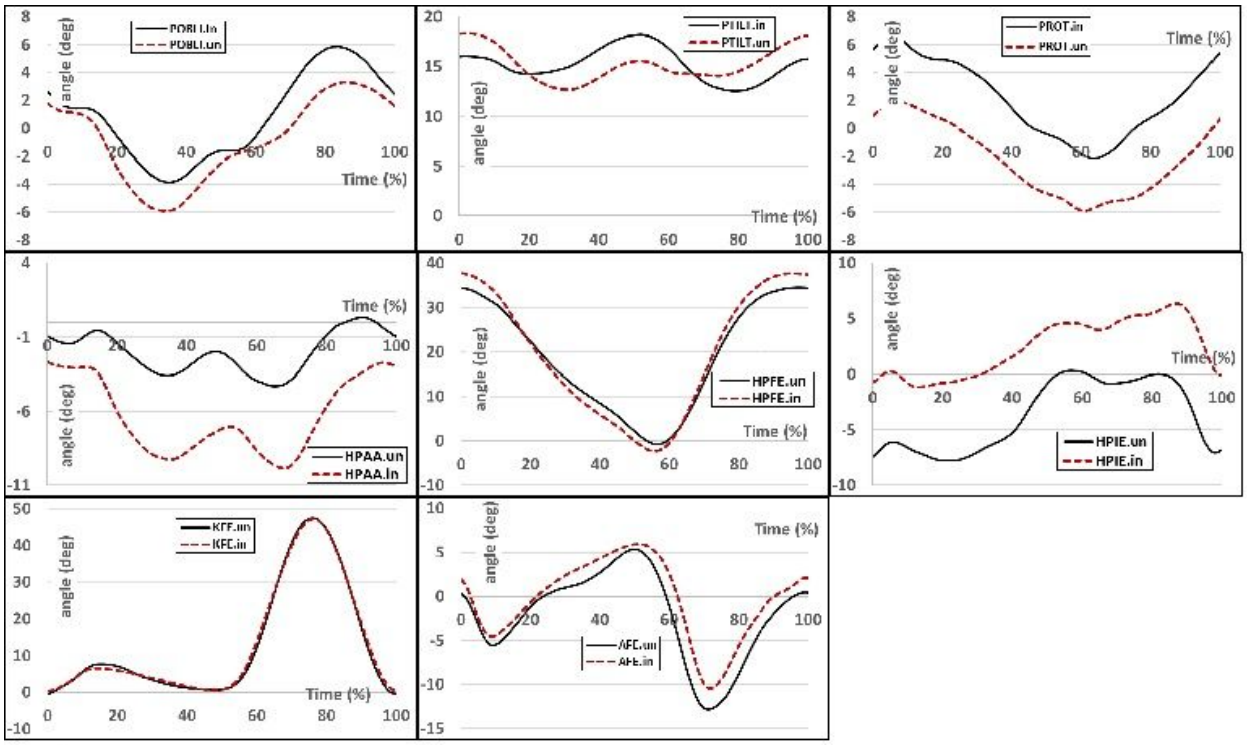

Figure 1.

Figure 1

Range of motion in main low extremity joints characterizing pelvic obliquity (POBLI), pelvic tilt (PTILT), pelvic internal/external rotation (PROT), hip ad/abduction (HPAA), hip flexion-extension (HPFE), hip rotation (HPROT), knee flexion-extension (KFE) and ankle flexion-extension (AFE). The curves represent how a single, angular variable varies over the gait cycle (expressed in %). The dark line represents the involved side, and the dashed red line represents the uninvolved side.

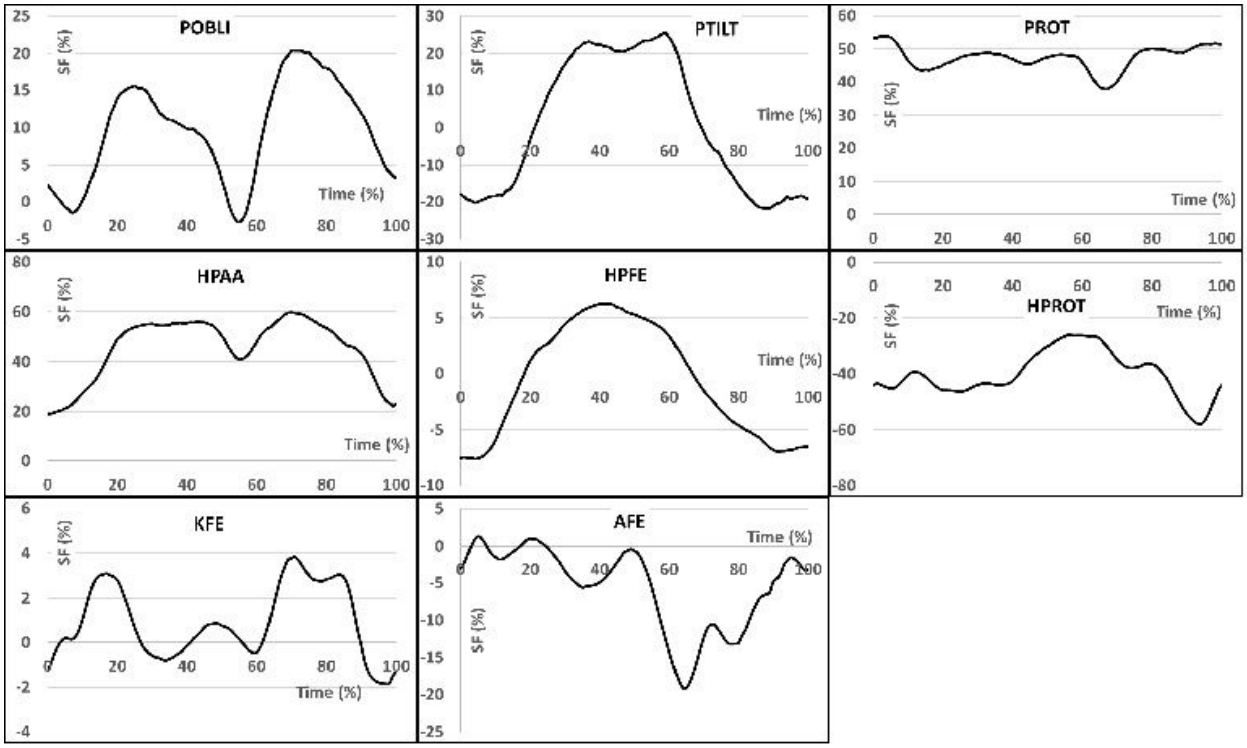

Figure 2.

Figure 2

Symmetry function curves for main lower extremity joints characterizing symmetry of pelvic obliquity (POBLI), pelvic tilt (PTILT), pelvic internal/external rotation (PROT), hip ad/abduction (HPAA), hip flexion-extension (HPFE), hip rotation (HPROT), knee flexion-extension (KFE) and ankle flexion-extension (AFE) as a function of normalized cycle time. The function represents the side difference in relation to its averaged range of change.

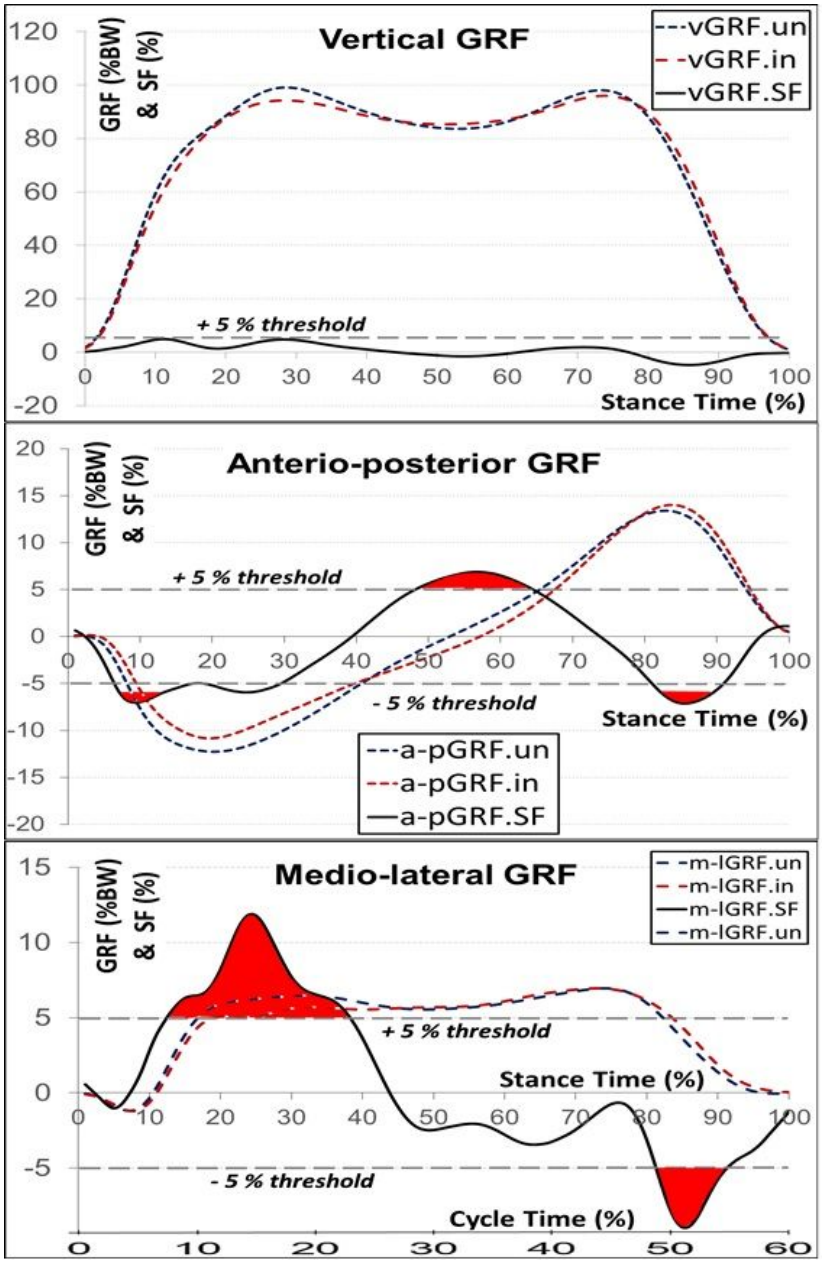

Figure 3

Side deviations of the main components of ground reaction function: vertical, anteroposterior and mediolateral for the involved (dashed red line) and uninvolved sides (dashed blue line) with corresponding symmetry function (solid dark line). The curves represent how a single variable varies over the gait cycle (expressed in %). Areas exceeding +/- 5% symmetry threshold are marked in red