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Original Article

Gait symmetry - A valid parameter for pre and post planning for total knee arthroplasty

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Abstract

Objectives: We aimed to determine whether GS can help to plan and rearrange the treated side by using IMUs to measure the joint angle of the hip, knee, and ankle. We hypothesized that the kinematics in healthy individuals for both sides are approximately equal during walking. **Methods:** IMUs were used to measure the joint angles of 25 healthy participants during walking. The participants performed the 10-meter walk test. The normalized symmetry index (SI_{norm}) was used to calculate the symmetry of joint angles for the hip, knee, and ankle throughout the gait cycle. **Results:** The SI_{norm} demonstrated high symmetry between both legs; and the ranges were -1.5% and 1.1% for the hip, -3.0% and 3.1% for the knee, and -12% and 9.2% for the ankle joint angle throughout the gait cycle. **Conclusion:** The SI_{norm} provides strong information that can be helpful in the planning process for the surgeries. Further, the IMUs system gives the possibility to measure the patients before their surgeries and use their data to plan and rearrange for the operated side.

Keywords: IMU, Gait Symmetry, Joint Angle, Symmetry Index, Therapy Planning

Introduction

Total knee arthroplasty (TKA) is a routinely used intervention for patients with end-stage knee osteoarthritis (OA)[1]. It is a commonly performed surgical procedure that is beneficial to the majority of recipients and is cost-effective for quality of life assessments[2]. The goals of TKA include pain reduction, returning to activities of daily living, restoring (mechanical) alignment, preserving the joint line, balancing the ligaments, and restoring a normal Q-angle[2]. Therefore, the non-operated limb is often used for planning the (geometric) reconstruction of the affected side[3]. Especially for kinematic and beside the mechanical alignment respectively, gait symmetry (GS) could be a possible parameter to plan and rearrange the destroyed side. By adopting the characteristics of the healthy leg to reconstruct the operated one. Furthermore, providing in-depth information about the lower extremities' symmetry is expected to improve the post-therapy rehabilitation quality and speed up recovery.

It seems that in the last two decades the interest in analyzing GS increased in parallel with the rapid development of new technologies that emerged into the field of biomechanics[4]. GS is generally defined as the identical behavior of the left and right limbs during gait[5]. Pronounced asymmetry levels have been associated with pathological conditions, such as lower-limb amputations, arthroplasties, OA, TKA, and stroke, as well as anterior cruciate ligament injury[6–8].

The gait analysis (GA) is important to confirm a functional diagnosis, which establishes the relation between dysfunction and movement pattern, providing a more holistic framework to design interventions[9]. Besides the usual kinematic parameters (i.e., flexion-extension angle, axial rotation, lateral bending), GS of these parameters is an important feature, which is usually qualitatively observed[10,11]. Numerous studies analyzed GS in different physical conditions and different groups. For instance, healthy individuals[12,13], the effect of orthopaedical orthosis[14], patients after surgeries or rehabilitation programs[15,16], medical emergency cases,

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and diseases[17,18] were evaluated. One example is the study of Aljehani et al.[3] who used symmetry to compare bilateral sagittal plane biomechanics between subjects with and without contralateral knee OA after unilateral TKA. Their finding was subjects with contralateral knee OA have more symmetrical gait, although they adopt a more abnormal and stiff-legged gait pattern bilaterally. Many studies used the symmetry index SI (Equation 1) to quantify the GS of spatial and temporal parameters[19–21], kinematic parameters[22], and kinetic parameters[23,24].

$$SI = \frac{2(X_a - X_u)}{(X_u + X_a)} \cdot 100 \quad \text{Equation 1}$$

The SI equation has modifications that were used depending on the parameters, medical case, and the type of comparison[25–27]. For instance, in Lugade et al.[16] the modified SI equation (Equation 2) was used, with X_a as the parameter of the involved leg and X_u as the parameter of the uninvolved leg, to calculate the symmetry between the operated hip and the non-operated hip.

$$SI = \frac{(X_a - X_u)}{X_u} \cdot 100 \quad \text{Equation 2}$$

Spatiotemporal parameters were analyzed in Chen et al.[28] with another modified SI equation (Equation 3) to calculate the symmetry of stroke patients based on the step length and the swing duration, with X_a of the paretic and X_u of the non-paretic leg.

$$SI = \frac{(X_a - X_u)}{\max(X_a + X_u)} \cdot 100 \quad \text{Equation 3}$$

The GS studies investigated several kinematic parameters (joint angles, velocities, etc.) through their trials (full gait cycle) whether the participants were patients or healthy individuals. For instance, Winiarski et al.[29] investigated the pelvic tilt angle and the flexion-extension angles for the hip, knee, and ankle joints for patients after unilateral total hip replacement. In another study from Nigg et al.[30], the angles and velocities of the three lower limb joints were investigated to evaluate a new methodology to quantify lower extremity movement symmetry using data from the stance phase in over-ground running for healthy individuals. As we can see from the previous examples, the joint angle and its velocity have been used to investigate different cases.

Furthermore, we can determine the range of motion (ROM) from the joint angle. ROM is one of the common kinematic parameters besides the mentioned ones, which is used to analyze GS[30]. The ROM is defined as the difference between the maximum and minimum angle drawn between two adjacent articular segments within one gait cycle[31]. The ROM symmetry can be calculated by using the SI[16]. Furthermore, there are different methods to measure the ROM, the approach to use inertial measurement units (IMUs) is one method, which detects the joint angles continuously during motion[32]. The IMUs have good features like portable, small, light sensors with three accelerometers, gyroscope, and magnetometer, to detect the orientation in space, and in case of biomechanical analysis of the segments, they are connected to[32–34]. In combination, IMU systems allow the measurement of anatomical joint angles in three dimensions between two equipped segments[35].

Table 1. Participant's demographics (mean ± standard deviation).

Number	25
Age (year)	26.7±3.6
Height (cm)	175.8±9.4
Weight (kg)	73.8±11.9
BMI (kg/ m²)	24±2.7

Measuring the joint angles and their symmetry for the bilateral limbs could indicate the dynamic situation between both legs. Therefore, it can help in therapy planning by supporting the surgeon in which the prosthetic model is needed for the surgery based on the results of the non-operated joint angles and both are symmetrical. Furthermore, providing quantitative symmetrical changes in the knee biomechanics of TKA patients pre, post-surgery, and during the rehabilitation period may help surgeons track recovery and enable the therapist to proactively design the phases of rehabilitation protocol following the patients' test results.

We aimed from this study to demonstrate whether symmetry of the kinematic parameter hip, knee, and ankle joint angles for healthy individuals, measured by using IMUs, can be assumed. In that case, GS information can be used for planning and rearranging for the operated leg and rehabilitation program in the subsequent period.

Materials and methods

Subjects

Twenty-five young healthy participants (14 males, 11 females), adults aging from 20 to 35 years, without any pathology were included in the study (Table 1). The following exclusion criteria were established: no previous history of either orthopedic or neurological ailments, such as a recent injury or surgery, which could affect their walking pattern. Furthermore, the right leg has to be the dominant leg, which was evaluated based on the gentle push test[36]. The participants were asked to stand in an upright position while both legs were on the same level, then a slight push towards forward was performed. The first leg compensates to prevent the body from falling will be the dominant leg.

Ethics approval

The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the Medical Ethical Committee (Ref. No. EK 121/17) of the Department of Orthopedic Surgery at University Hospital RWTH Aachen. Informed consent was obtained from each subject.

Measurement's setup

To track the movements, seven IMUs from the MyoMotion system (Noraxon U.S.A. Inc., Scottsdale, USA) were used. The sensors were attached with elastic straps or tape to the pelvis and both thighs, shanks, and feet of each participant (Figure 1). The essential use of the system is to quantify angular changes of the involved joints typically in 3 degrees of freedom (3DOF). This can be done by deriving mathematically transitive components from linear acceleration data and inverse kinetic modeling[37]. For joints angles calculation, at least two sensors needed to be located around a joint[38]. The joint angles were calculated based on the medical neutral-zero-method. It is the essential principle which indicates that in a normal upright standing position all joints are at the zero position, even if they already have an offset angle. The joint angles of the hip, knee, and ankle were recorded continuously with a sampling frequency of 100 Hz[37].

Figure 1. The position of the seven MyoMotion sensors. The pelvic sensor was attached to the bony area of the sacrum. The thigh sensors, they were attached in the frontal side on the lower quadrant of the quadriceps, slightly above the kneecap, and area of lowest.

Testing procedure

In the beginning, each participant was asked to stand still in an upright position (neutral zero joint position) to calibrate the IMU system. In a normal upright standing position, all joints are defined to be in the neutral position, even if they already have an offset angle. After calibration, the participants had to fulfill a 10-meter walk test (10MWT) with self-selected speed. The 10MWT is an individual walking test with or without assistance over 10 meters and the time is measured for the intermediate 6 meters to avoid acceleration and deceleration[39]. Each participant was asked to do a test trial, to be familiar with the test.

Data processing

Data processing was done with the MyoMotion software MyoResearch (version MR 3.12, Noraxon U.S.A. Inc., Scottsdale, USA). The mean of two strides for the left and right sides was calculated to present the data over one (left and right) gait cycle. The first and the last two strides of the 10MWT were excluded to avoid the acceleration and deceleration in gait. To define the strides the contact mode of the MyoResearch software was used, which uses the accelerometer data of the IMUs on the feet to evaluate initial and terminal feet contact and creating a virtual foot contact signal for the left and right side. MyoResearch presented the data over a time normalized gait cycle, running from 1 to 100% (100 data points per gait cycle). This time normalization allowed a standardized comparison of records that automatically eliminates the unavoidable timing differences[40].

The data were exported from MyoResearch to Excel (2016, Microsoft, USA), for further data processing. Based on the full angle curves over one gait cycle of the hip, knee, and ankle motion in the sagittal plane (flexion and extension, respectively dorsi- and plantarflexion), the following calculations were performed. As a first step, the angle curves were min-max normalized (Equation 4) to transform the angular values larger than one. For each joint, the normalized joint angle curves were calculated for the left and right sides, with θ_n as the joint angle in [°] on time point n=1,2, ...to 100% of the gait cycle and θ_{min} and θ_{max} as the maximum and minimum measured joint angle during the gait cycle. In contrast to Gouwanda et al.[41–43], the maximum and minimum joint angle of the appropriately analyzed angle curves were used, and not only the values of the right gait cycle.

$$\theta_{norm(n)} = \frac{\theta_n - \theta_{min}}{\theta_{max} - \theta_{min}} + 1 \qquad \text{Equation 4}$$

Based on the normalized joint angle (θ_{norm}), the SI_{norm}, as a modified version of *SI*[43], was calculated. The SI is prone to artificial inflation in the case of values in the range of 0[44], which makes it difficult to interpret the GS of joint angles over a complete gait cycle. SI_{norm} is computed as (Equation 5):

$$SI_{norm} = \frac{\theta_{Rnorm(n)} - \theta_{Lnorm(n)}}{0.5\,(\theta_{Rnorm(n)} + \theta_{Lnorm(n)})} \cdot 100\% \qquad \text{Equation 5}$$

with the normalized joint angle of the left θ_{Lnorm} and right θ_{Rnorm} side. The SI_{norm} was used to quantify the lower limb symmetry in the hip, knee, and ankle joints. Finally, based on literature the gait cycle was defined by time percentage for the two phases, the stance phase which extends from 0-60%, and the swing phase which extends from 60-100% from the gait cycle[41,42]. For visualization, the curves were presented with the help of IBM® SPSS Statistics (IBM® SPSS Statistics v. 25, IBM Cooperation,

Table 2. Descriptive statistics of the analyzed joint angles.

Joint angle	Phase	N	Min in °	Max in °	Mean in °	SD in °
Max. hip flexion	RT-Stance	25	13.6	48.2	28.1	7.4
	LT-Stance		11.9	42.3	29	6.5
	RT-Swing		22.8	55.1	34.1	6.9
	LT-Swing		24.1	46.4	35.5	5.3
Max. knee flexion	RT-Stance		24.4	54.5	39.3	7.8
	LT-Stance		25.7	48.7	36.3	5.8
	RT-Swing		54.2	82.6	70.8	5.9
	LT-Swing		62.2	96.8	72.1	6.4
Max. ankle dorsiflexion	RT-Stance		1.1	20.8	11.9	11.6
	LT-Stance		0.8	19.1	8.7	4.3
	RT-Swing		-5.8	11.6	1.3	3.8
	LT-Swing		-12.7	21.4	-3.4	5.8

Table 3. Descriptive statistics of the maximum absolute normalized symmetry indices of the respective joint angles in the sagittal plane during the stance and swing phase.

SI_{norm} minimum						
Joint	**Phase**	**N**	**Min in %**	**Max in %**	**Mean in %**	**SD in %**
Hip	Stance	25	-13.77	-1.15	-6.42	3.5
	Swing		-12.97	-0.96	-5.90	3.5
Knee	Stance		-21.98	6.67	-9.58	6.4
	Swing		-38.62	-0.02	-10.77	11.2
Ankle	Stance		-55.90	-1.04	-21.14	15.1
	Swing		-44.81	-2.69	-15.19	11.1
SI_{norm} maximum						
Joint	**Phase**	**N**	**Min in %**	**Max in %**	**Mean in %**	**SD in %**
Hip	Stance	25	0.57	19.83	6.97	4.3
	Swing		0.17	16.75	5.63	4.1
Knee	Stance		-2.66	14.72	5.48	4.5
	Swing		-4.75	19.96	6.35	5.6
Ankle	Stance		1.61	37.35	13.15	8.7
	Swing		1.06	61.48	18.59	13.0

Chicago, Illinois, USA). In these descriptive statistics, we preferred to show the main two phases (stance and swing) without the subphases (initial contact, midstance, ... etc) to give a comprehensive overview of the gait cycle. The maximum joint angles for the hip, knee, and ankle in the sagittal plane were calculated for the stance and swing phases. Further, the minimum and maximum of the normalized symmetry indices were calculated. In both cases, descriptive statistics (minimum, maximum, mean, and standard deviation) of the parameters were presented for all participants.

Results

Table 2 demonstrates the minimum, maximum, mean, and SD values of the maximum joint angles in the sagittal plane for the stance and swing phases during the gait cycle.

Table 3 demonstrates the descriptive statistics of the minimum and the maximum of the normalized symmetry indices of the three joint angles in the sagittal plane during stance and swing phases. The highest asymmetry values of the minimum SI_{norm}, with increased flexion of the left leg compared with the right leg, were in the ankle stance

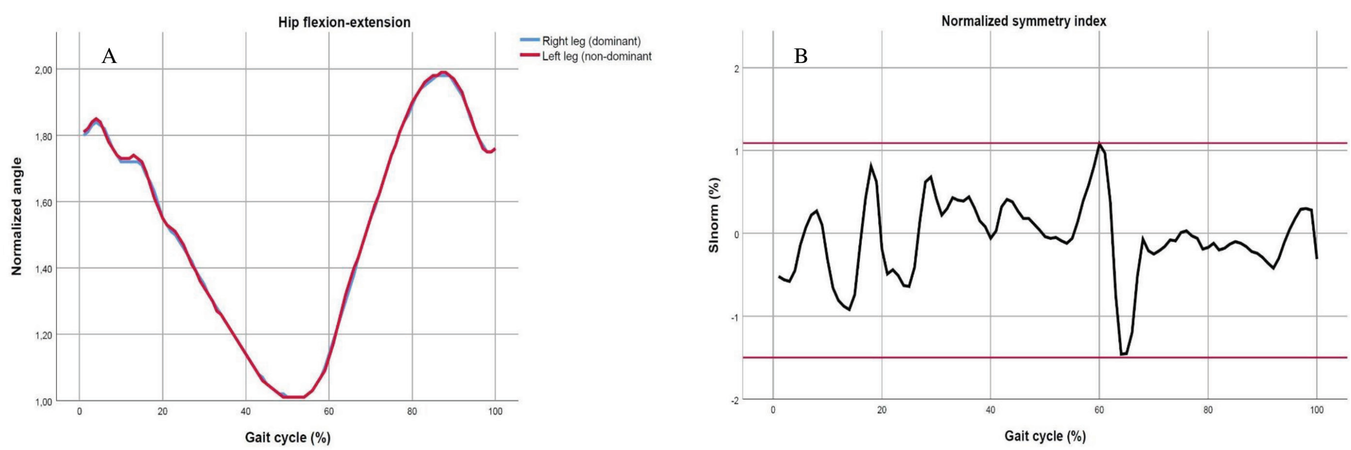

Figure 2. The normalized mean curves for the hip flexion- extension (A) and the normalized symmetry index of this parameter (B). The dominant (right) leg is presented in the blue color, and the non-dominant (left) leg in red color.

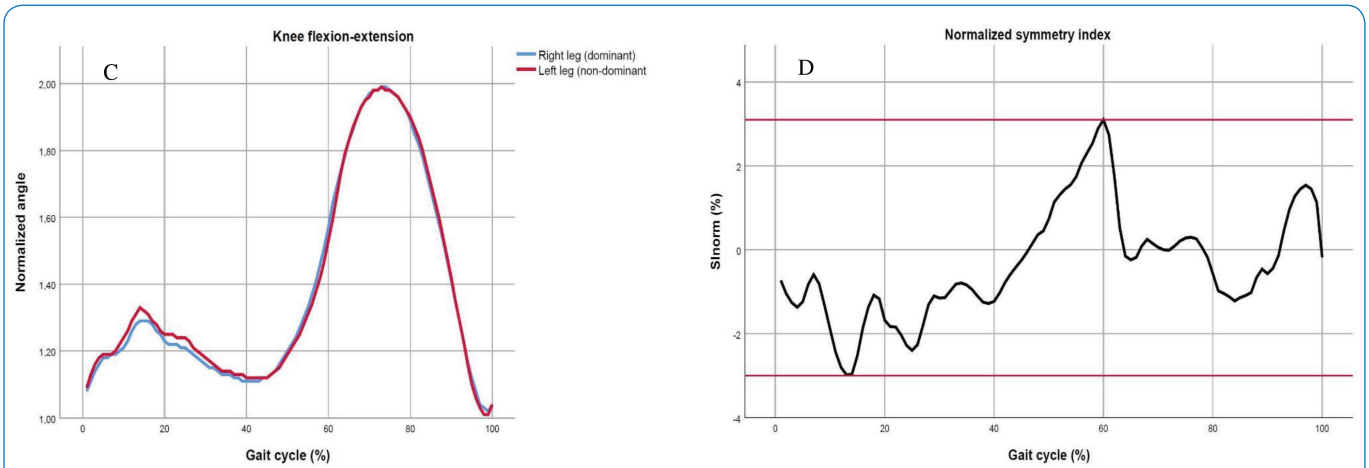

Figure 3. The normalized mean curves for the knee flexion-extension (C) and the corresponding normalized symmetry index (D). The dominant (right) leg is presented in the blue color, and the non-dominant (left) in red color.

and swing phases with -55.90 and -44.81 respectively. Furthermore, the highest asymmetry of the maximum SI_{norm}, with increased flexion of the dominant right leg, was also in the ankle joint with 37.35 in the stance, and 61.48 in the swing phases.

Figures 2-4 depict the normalized curves for the left and right hip, knee, and ankle movement over one gait cycle and the appropriate SI_{norm} curves. The normalized hip angle of the dominant and non-dominant leg had nearly similar values (Figure 2A). In accordance, the SI_{norm} for the hip was ranged between -1.5% and 1.1% throughout the gait cycle (Figure 2B). The hip SI_{norm} curve showed the highest asymmetry values during the initial swing period (60-73%) (Figure 2B).

Analyzing the normalized knee angle curve (Figure 3C), in most of the stance phase the non-dominant leg had higher values than the dominant leg (0-50%). On the other hand, in the late stance and early swing phase, the dominant leg showed higher values than the non-dominant leg (50-66%). In the remaining swing phase, both legs showed similar values (66-100%). The SI_{norm} for the knee was ranged between -3.0% and 3.1% throughout the gait cycle (Figure 3D). On the other hand, the knee SI_{norm} showed the highest asymmetry values in two different periods (Figure 3D), the first maximum was during the midstance period (10-30%), the second value was during the initial swing period (50-73%).

In the normalized ankle angle curve (Figure 4E), the same situation as for the knee angle is visible, the non-dominant leg showed higher values than the dominant leg in most of the stance phase (0-50%). In the late stance and early swing phase, the dominant leg showed higher values than the non-dominant leg (50-66%). In the remaining swing phase, both legs showed similar values (66-100%)

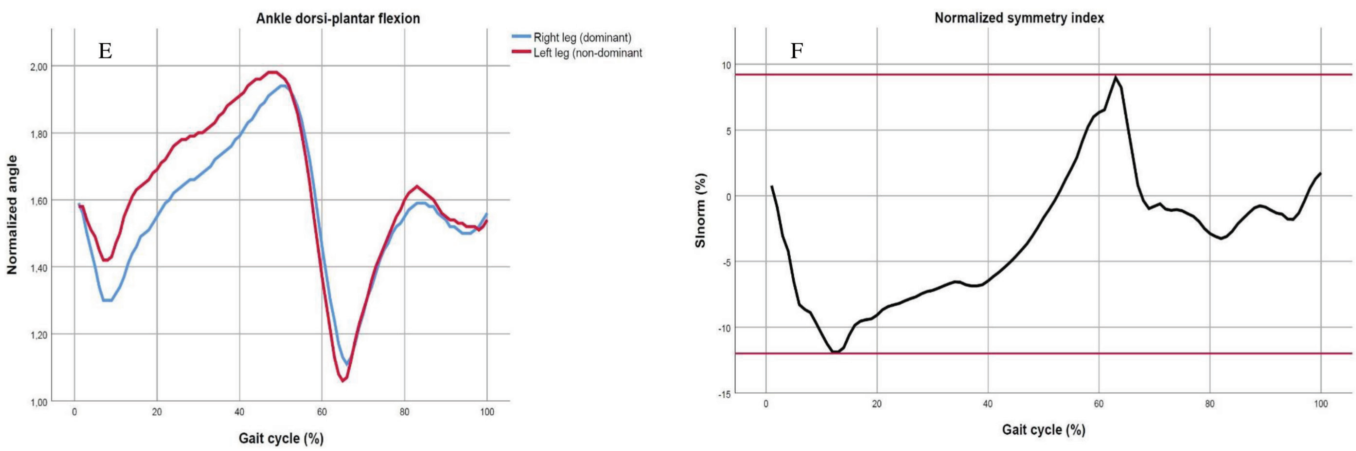

Figure 4. The normalized mean curves for the ankle dorsi- and plantarflexion (E) and the corresponding normalized symmetry index (F). The dominant (right) leg is presented in the blue color, and the non-dominant (left) leg in red color.

The SI_{norm} for the ankle was ranged between -12% and 9.2% throughout the gait cycle (Figure 4F). Furthermore, the ankle SI_{norm} showed the highest asymmetry values in two different periods (Figure 4F), the first period was during the midstance (10-30%), and the second period was during the initial swing (55-65%).

The highest common SI_{norm} values between the two legs were around 60%, which was in favor of the dominant leg for the three joints (Figure 2-4). The hip and knee joints shared the same period that had the highest asymmetry values which were during the late stance phase 50-73%. On the other hand, the ankle joint had the highest asymmetry values during the early swing phase. Furthermore, for the knee and ankle, SI_{norm} shared other high values which were during the midstance period.

Discussion

The outcome of our study supported our hypothesis that the kinematics of both sides were approximately equal in healthy individuals. The symmetry of hip, knee, and ankle movement in the sagittal plane was shown with SI_{norm} values never exceeding 12% during the whole gait cycle. Therefore, GS, calculated as the SI_{norm} of the three joint angles, seems to be a suitable and helpful parameter for planning and rearranging for TKA surgery.

In the beginning, we focus on the analysis of the lower limb movements (joint angles) in the sagittal plane due to many factors; first, walking mostly happens in the sagittal plane[33,45]. Second, the sagittal ROM is considered an important parameter for clinical evaluations[46]. Third, each joint has an important role during gait in the sagittal plane[47]. The hip movement allows the forward progression of the limb and maintains the pelvis and the trunk[47]. The knee movement maintains stance stability and allows shock absorption[47]. Finally, the ankle movements are important for normal coordinated gait, and regulate the movement of the center of mass[47]. It allow the foot to accommodate different grounds, provides shock absorption, and also acts as a rigid segment for the propulsion of the body during the second double support[47].

We infer from the above results that the joint angles during walking are almost similar and symmetrical for healthy individuals, corresponding with the outcome of Patterson et al.[23]. Our results support that able-bodied people show minimal laterality with only subtle differences between the dominant and non-dominant leg based on kinematic parameters. Therefore, our hypotheses that joint angles can be used to help the surgeon to adapt the healthy leg as a reference to plan for the operated leg is further supported. In our results, the SI_{norm} indicates a slight difference between the right and left leg. The SI_{norm} of the hip flexion-extension ranged between 1.1% and -1.5%, which was lower than the symmetry values of ±15% evaluated by Gouwanda et al.[41,43] for the thighs angular velocity of healthy individuals. For knee flexion-extension, the results showed SI_{norm}-values ranged between 3.1% and -3.0%, which were also lower than the values of the shanks angular velocity (range from 15% to -30%, and 15% to -15% respectively) shown by Gouwanda et al.[41,43]. Compared to the presented hip and knee symmetry values, the SI_{norm} for the ankle dorsi-plantarflexion showed a higher asymmetry with a range between -12% and 9.2%. In addition to the different range of SI_{norm}-values compared to the results of Gouwanda et al., differences in the progression of the SI_{norm} over the gait cycle can be observed. A reason for the observed differences could be in the differences between segments angular velocity analyzed by Gouwanda et al. and the joint angles. Further studies are necessary to analyze symmetry differences of specific measured movement parameters. In addition, the effects of the study population and measurement systems can be reasonable for small differences that need to be analyzed in further studies.

The range of asymmetry seen above in the different joints is considered as 'imperfect' symmetry which can be contributed to higher muscle strength in the dominant leg than in the non-dominant leg[48–50]. Muscle strength is one of the essential factors in body movement and especially walking movement[50,51]. Furthermore, the study of LaRoche et al.[52], showed that GS is lower in older women with strength asymmetry more than older women with strength symmetry, and it decreases when they walk near their maximal capacities. We believe that the difference in muscle strength between both legs was the reason for the asymmetry in gait. The highest SI_{norm}–values were found in the late stance and early swing which is clearly appeared between 50-73% from the gait cycle, with a peak at 60% of the gait cycle for the hip and knee SI_{norm} and at 65% for the ankle joint SI_{norm} always in favor of the dominant leg. Regarding the hip joint, the movement during the pre-swing period is initiated with recovery from hyperextension from the previous terminal stance period[53]. The stronger muscles of the iliacus and rectus femoris in the dominant leg will increase the hip flexion (thigh advancing) more than the non-dominant due to the stronger contractions which flex the thigh more. Furthermore, this movement situation will increase the rapid passive flexion of the knee and the ankle joints in the dominant leg. The impact of the hip muscle strength of the dominant leg affected the same gait period for the knee and ankle. Moreover, the high values of the non-dominant leg in the midstance period for the knee and ankle joints could be related to the previous pre-swing situation in the dominant leg. The pre-swing period of the dominant leg, where the thigh advances forward, is simultaneously together with the midstance phase of the non-dominant leg. The dominant leg with more power and speed will force the two joints of the non-dominant leg to extend slightly more than the two contralateral joints. The summary is that the stronger leg (dominant) is influencing the gait cycle by affecting the bilateral legs movement. In case of a large difference in muscle strength appears between both legs, which may lead to a higher range of motion in favor of the non-dominant leg. A higher flexion prosthesis would be a better choice for the surgery to compensate for the large difference in the range of motion between both legs.

However, when considering each joint separately, it is apparent that the range of symmetry of the three joints is different, as shown in our results. We refer this to the anatomical structure and location for the hip joint, which is surrounded and supported by big and strong muscles[53]. These muscles cooperate easier and faster to compensate for the muscular strength deficit in one muscle or more if it occurs during the performance compared to the other side. That supports the concerned hip to reach a closer joint angle to the other side. For the knee joint, the anatomic structure affects the asymmetry between both legs, with less muscles working on the joint, the compensation would be decreased which allows for more movement in the joint.

In the case of the ankle joint, which showed the highest asymmetry between all joints, the anatomical structure influence increases further where smaller muscle surrounding the ankle joint than the hip and knee joints, compensate even further, leading to higher joint angles in case of muscle strength weakness. To highlight the influence of the anatomical structure on the GS, which is based on the SI_{norm} for lower limb joint angles in the sagittal plane. The GS limits showed higher symmetry in the hip, knee, and ankle, respectively. This information will provide the surgeons with a hint on how to deal with the joint in case of reconstruction surgery.

Back to our findings, who underline symmetric gait in healthy subjects, GS seems suitable for surgery planning. For the knee joint the results showed that the surgeon can choose the more suitable prosthetic model for the surgery based on the non-operated joint ROM, due to the point that there are different models of a knee prosthesis with a different ROM for each model. For instance, varied studies investigated the different models the posterior stabilized (PS) implant had higher ROM than cruciate-retaining (CR) 145° vs 125° respectively[54]. While the high-flexion PS and CR have 155° of flexion[54]. In another study by Seon et al, the high-flexion PS implant showed higher ROM than high-flexion CR 126.3° vs 115° respectively[55].

For rehabilitation reasons, it was found by reviewing the previous literature that asymmetric gait is associated with several negative consequences, such as gait inefficiency, challenges to balance control, risk of musculoskeletal injury to the non-paretic lower limb, and loss of bone mass density in the paretic limb[56,57]. That supports our theory that GS could help in arranging the therapy plan based on the symmetry test results which can be performed before and after the rehabilitation period. By leading the therapist to which exercises are needed for each patient (walking symmetry exercises, strength, range of motion, etc) through the different rehabilitation periods. Furthermore, it can help the therapist to prevent any complications within the operated leg which can lead to revision surgery, or to prevent any development of OA in the contralateral leg in the future. This can appear in the preparation phase after TKA. By setting up specific rehabilitation programs e.g. strength exercises as it has been applied in the study of Bazyler et al.[58], and Ebert et al.[59], or modified program as in Rapp et al.[60], which decreased the asymmetry that results from the compensation (load) between the two legs.

Our findings could be used as a normal range of symmetry for lower extremities, in which the clinicians and therapist can build up their test results. The symmetry limits for each joint are ±1.5% for the hip, ±3.1% for the knee, and ±12% for the ankle. These limits will help the patients to focus on the exercise to regain his/her normal gait pattern, and for the surgeon to follow up on the surgery improvement.

Moreover, our findings showed that IMU systems could be helpful in dynamic motion analysis to evaluate GS and support the surgical decision. By providing more information about joints motion during walking, will lead to more understanding of each joint's condition and movement. Furthermore, it will give the surgeons the chance to see the gait cycle and define the deficits in it.

Nevertheless, we were able to evaluate the GS of healthy participants on kinematic parameters, based on SI_{norm} values for the hip, knee, and ankle joint in a range under 15%. Therefore, GS seems to be a suitable parameter for TKA surgery planning. In future work, the symmetry of gait kinematics in other movement planes is of interest.

The study comes along with limitations. First, there was a factor that had a limitation effect on our study which needs to be mentioned. The signal recording wasn't optimal in a couple of trials, especially the ankle records due to the surrounding environment in the hallway in the University hospital (cables underground, neon lights, metal, and wifi signal. Second, in this study, we analyzed healthy participants instead of patients before or after TKA. The future plan is to work on patients. Third, we analyzed the kinematic parameter for the hip, knee, and ankle in one plane (sagittal plane). Also, we analyzed one movement which is walking forward in 10 meters".

Conclusion

We conclude that the normalized symmetry index SI_{norm} for hip, knee, and ankle motion in the sagittal plane demonstrated high symmetry between both legs in healthy individuals. GS of joint angles can be assumed in healthy individuals during walking, with a range of ±15% of the SI_{norm}. Therefore, the results on the GS provide solid information that can be helpful in the planning process for the surgeries and the rehabilitation program post-surgery. A relevant point, IMUs system can be used to measure the patients before their surgeries and use their data to plan and rearrange for the operated side.

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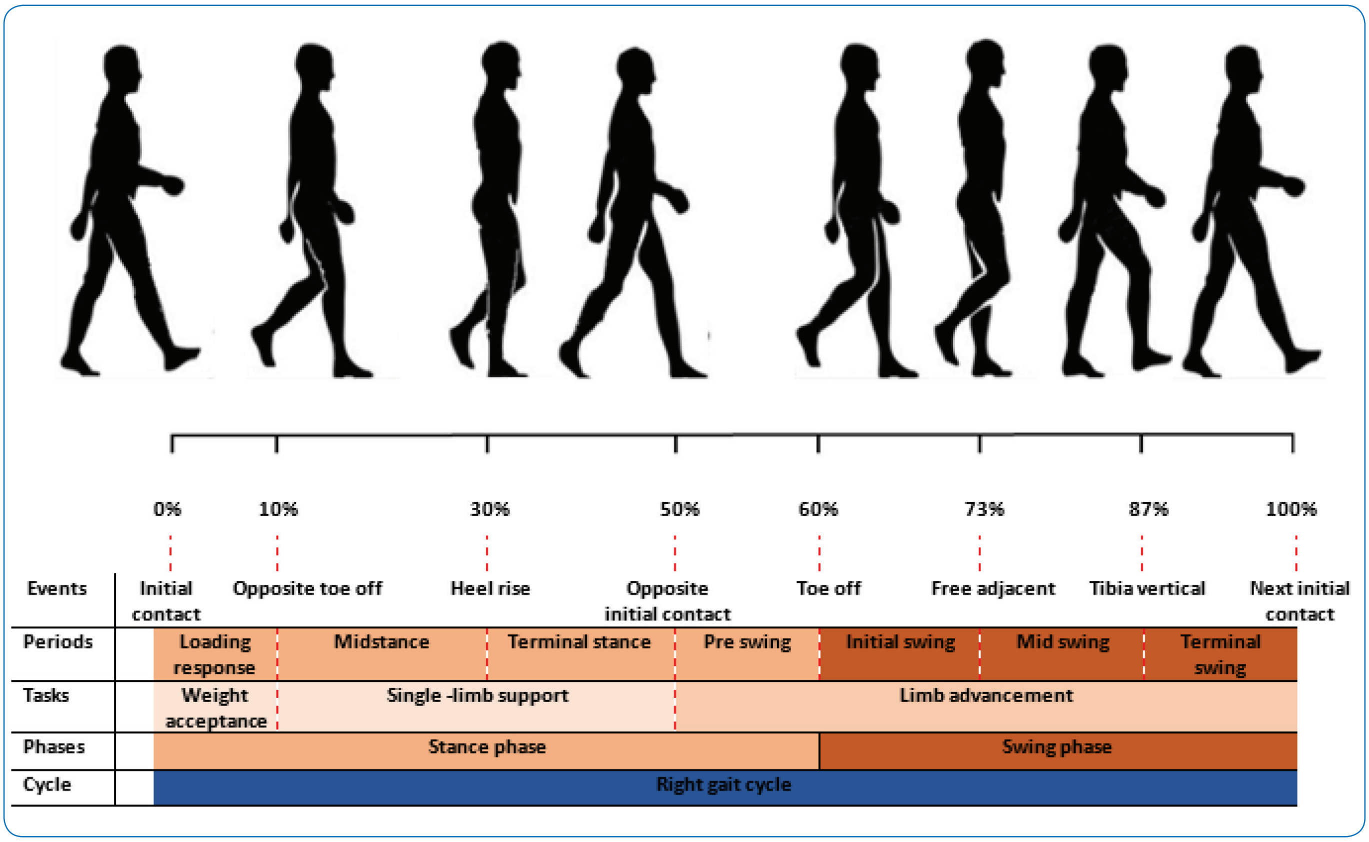
Appendix: Gait map



Supplementary Figure. The subdivision of the gait cycle for the right leg during walking.