Development of a Lower Limb Gait Asymmetry Index with Cyclogram Analysis Using Image Processing

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***Abstract*—This study focuses on developing a gait asymmetry index and applying image processing techniques to cyclogram analysis. We evaluated gait asymmetry under different walking conditions, specifically examining the effects of wearing a knee brace and holding a weight in hand. Using inertial measurement units (IMUs), we collected gait data to analyze knee, hip, and ankle angles in the sagittal plane. The joint kinematics data were assessed using our proposed asymmetry index, which combines image processing techniques and linear regression models. The proposed asymmetry index incorporates cyclogram area, trend symmetry, and the longest length of the cyclogram shape, effectively capturing variations in symmetry and providing a comprehensive measure. The results demonstrate that the proposed asymmetry index can effectively distinguish between different gait conditions. The findings potentially offer insights for researchers and clinicians in human biomechanics, aiding in the planning of interventions and the assessment of motion patterns, as well as for developers of bipedal walking robots in the field of robotic locomotion, enhancing their ability to design hardware and evaluate motion patterns.**

***Index Terms*—Biomechatronic systems, asymmetry index, motion capture system, image processing, gait analysis.**

I. Introduction

The gait of humans and bipedal walking robots is a complex and coordinated process involving the intricate interaction of multiple limb segments and joints. These segments and joints follow a cyclic and typically symmetric movement pattern during normal locomotion. However, certain conditions, particularly those affecting the lower limb, can disrupt this symmetry, leading to an asymmetric gait [1]. This disruption often manifests as limping or other compensatory movements as the individual attempts to maintain mobility. Assessing gait asymmetry is crucial in clinical practice because it provides valuable insights into the severity of an injury, the impact on mobility, and the progress of recovery [2]. Traditional gait analysis often involves a combination of qualitative visual inspection and quantitative measurements, each contributing to a comprehensive understanding of gait abnormalities. However, subtle asymmetries may not always be evident through visual inspection alone, underscoring the importance of precise, quantitative assessment tools such as inertial measurement units (IMU) [3], [4].

Numerous indices have been developed to quantify gait asymmetry, each designed to highlight specific aspects of the gait cycle. These indices typically calculate the difference between left and right limb parameters, providing a measure of asymmetry. Cyclogram diagrams, which visually represent the relationship between joint angles throughout the gait cycle, offer a more holistic approach by integrating multiple dimensions of movement [5]. As an example, Pau *et al.* [6] used cyclograms to evaluate gait asymmetry in Prader-Willi Syndrome (PWS). PWS individuals show greater inter-limb asymmetry at the hip and knee joints, demonstrating the effectiveness of cyclogram analysis in assessing motor impairments. Moreover, Alves *et al.* [7] introduced the Weighted Universal Symmetry Index (wUSI) for detecting ground reaction force asymmetries, both in healthy individuals and those with artificially induced asymmetry. This continuous index is a sensitive tool for analyzing gait asymmetry, with potential applications in assessing pathological gait and monitoring rehabilitation progress. These measures are widely used in clinical settings to assess conditions like stroke, cerebral palsy, and lower limb injuries, helping clinicians track the effectiveness of interventions and monitor recovery [8], [9]. Despite their utility, many existing indices focus on univariate parameters, such as step length or joint angles, which may not fully capture the complexity of gait.

Previous studies have explored the effects of external factors, such as wearing a knee brace [10] or carrying a weight in the hand [11], [12], on gait asymmetry. These studies have shown that such factors can significantly alter gait patterns, either intensifying or masking underlying asymmetries. For example, Yap *et al.* [13] examined the impact of asymmetrical gait induced by a unilateral knee brace on knee flexor and extensor muscles, highlighting changes in knee joint angle and moment during gait phases, as well as differences in muscle forces between normal and braced knees. Similarly, Wu *et al.* [14] discussed the early detection of gait asymmetry using a dual-channel hybrid deep learning model with wearable sensors, where a controlled ankle motion boot was used to simulate different levels of asymmetry by adjusting the angle of the automatic chuck. Additionally, Dong *et al*. [15] proposed a model to evaluate lower limb symmetry during upper limb loading, using a classifier and dynamic time warping (DTW) algorithm to quantify and assess gait symmetry under various weight-bearing conditions. Understanding these effects is crucial, especially in clinical settings where accurate gait asymmetry assessments are vital for diagnosing conditions and planning effective interventions. However, existing methods often fall short of capturing the complexity of these interactions, underscoring the need for more advanced assessment techniques.

In response to the challenges mentioned earlier, this study introduces a gait asymmetry index that leverages image-based cyclogram analysis to provide a more detailed and comprehensive assessment of lower limb movements. This index incorporates multiple parameters, including cyclogram area, trend symmetry, and the most extended length of the cyclogram shape, to effectively capture variations in symmetry. By applying this new index, we aim to offer deeper insights into the effects of wearing a knee brace and holding a weight in hand on gait patterns. The findings from this study have the potential to enhance clinical assessments and improve the understanding of gait asymmetry, ultimately contributing to better patient outcomes.

The paper is structured as follows: Section II delineates the employed methodologies for deriving the asymmetry index, elucidating the procedures implemented during the study trials, and detailing the data collection process. Section III is dedicated to presenting the obtained results, and critically discusses these findings. Finally, Section IV encapsulates the paper by concisely summarizing the primary discoveries and their broader implications.

II. Methods and Materials

A. Experimental Procedure and Dataset

This study utilized a publicly available dataset [16], which includes motion capture data from participants performing various walking tasks under controlled conditions. The data collection procedure involved participants walking along an oval path under two-speed conditions: normal walking speed and fast walking speed. The dominant leg's movement was constrained using a knee brace to induce asymmetries, and participants held a 1 kg weight in the dominant hand. The knee brace and weight used in this trial are illustrated in Fig. 1. A simple illustration of this experimental procedure, showing walking with a knee brace and weight in hand, is provided in Fig. 2. Four distinct tasks were designed: walking without any additional weight or knee brace, walking with added weight in hand, walking with a knee brace, and walking with both weight and knee brace. Participants completed all tasks under both normal and fast walking speed conditions. Each participant walked along the oval path four times. Kinematic joint data were captured by a motion capture system, with

(a) (b)

Fig. 1. (a) The knee brace and (b) the weight used to restrict the joint range of motion.

Fig. 2. A schematic of the trial, which is walking with a knee brace and holding a weight in hand.

ten sensors placed on the participant's body at the hip, knee, ankle, shoulder, pelvis, and trunk. This study used lower limb angles at normal walking speed for asymmetry analysis in all four conditions.

B. Participants

The dataset comprises data from eleven healthy individuals (six males and five females) with an average age of 21.5 years (standard deviation: 3.0), a mean height of 1.71 m (standard deviation: 0.10), and an average weight of 64.33 kg (standard deviation: 9.24). All participants were free from gait impairments and had no significant history of lower extremity or joint trauma. Additionally, they were proficient in treadmill walking. Cognitive baselines were ensured by maintaining consistent scores among all participants on the Mini-Mental State Examination (MMSE). Prior to participation, all individuals provided written consent, permitting the public release of their data.

C. Asymmetry Analysis with Cyclograms

In this study, specific walking conditions were examined, including walking at a normal pace without any additional

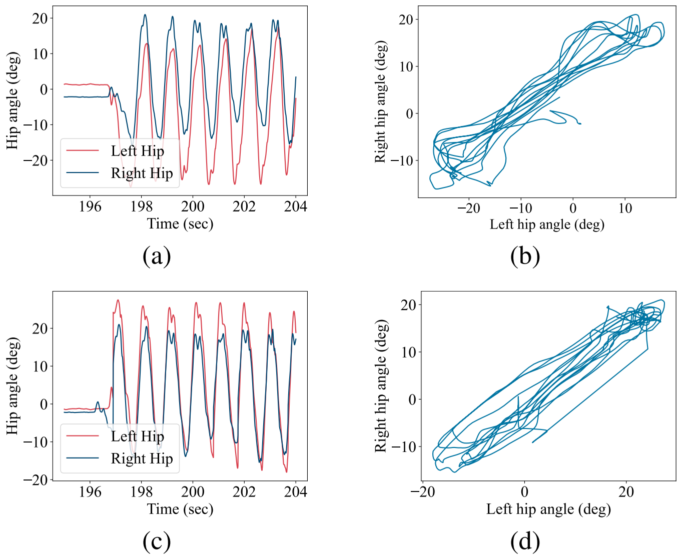


Fig. 3. Example of unsynchronized data for a normal walking task: (a) Left and right hip angles over time, and (b) the corresponding hip-hip cyclogram diagram. After synchronization and outlier and offset removal: (c) Left and right hip angles over time, and (d) the corresponding hip-hip cyclogram diagram.

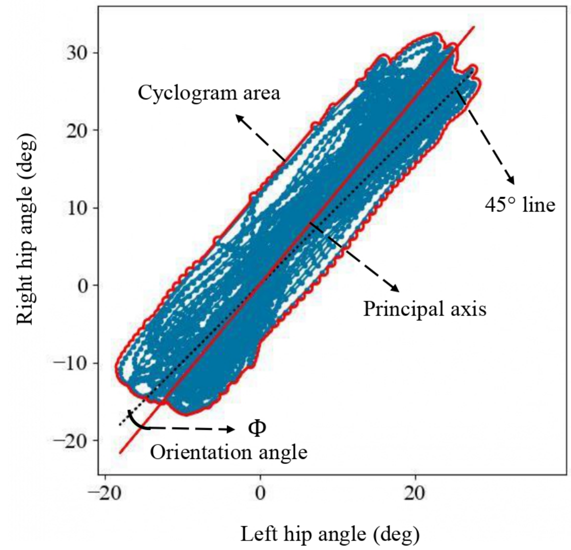


Fig. 4. Visual depiction of a cyclogram, highlighting essential features relevant to this study.

tools, walking with a knee brace, walking while holding a weight in hand, and walking with both a knee brace and a weight. Kinematic data were acquired during these walking conditions. Joint kinematic data of the knee, ankle, and hip angles were used to plot cyclogram diagrams. Initially, the left and right joint data were synchronized [17], [18]. After synchronization, outliers and offsets were removed. A sample comparison of data before and after synchronization for the normal walking task is illustrated in Fig. 3. Following this preprocessing, cyclogram diagrams were generated for all conditions and participants. To assess asymmetry in different walking conditions, several parameters were extracted from the cyclogram diagrams:

Cyclogram Area: represents the area of the angle-angle diagram [19]. There are several ways to estimate this area, such as fitting an ellipse to the shape or using the convex-hull method. To calculate this area accurately, the joint kinematic data were plotted and saved as an image. Image processing techniques were then employed to identify the shape's boundary by finding its contours. The largest contour was selected as the boundary, as illustrated by the red line around the shape in Fig. 4. The closed curve area was then computed using the Shoelace formula, with a smaller area value indicating greater symmetry.

Cyclogram Orientation: is rigorously defined as the absolute value of the angle ϕ, formed by the 45-degree line representing ideal interlimb symmetry and the orientation of the principal axis of inertia. This axis corresponds to the minimum moment of inertia within the cyclogram, as described in [20]. To determine the orientation, the direction of the eigenvector of the inertia matrix within the x-y reference system (left joint angle–right joint angle axis) is calculated. Lower values of this angle indicate a higher degree of interlimb symmetry. The next step involves fitting a line to the angle-angle diagram and comparing it to the reference line using linear regression. This method effectively models the shape and allows for a comparative analysis to define asymmetry. A graphical explanation is provided in Fig. 4 for more details.

Trend Symmetry: is a dimensionless parameter that quantifies the similarity between two waveforms, specifically the time-normalized angular trends of the right and left legs across gait cycles for each joint of interest. An eigenvector analysis, as detailed in [21], assesses the ratio of variability about the eigenvector to the variability along the eigenvector. Importantly, this measure is not influenced by waveform shifts or differences in magnitude. A value of 0 signifies perfect symmetry, while increasing values of trend symmetry correspond to greater asymmetry.

Proposed Asymmetry Index: This index is derived by combining three parameters from the cyclogram diagram: the area of the angle-angle diagram, trend symmetry, and the longest length of the cyclogram shape. The length is calculated by finding the intersection between the fitted line of the cyclogram shape and the boundary of the shape. This ensures an accurate measurement of the longest axis, which is essential for assessing the overall range of joint movement. The equation for the Asymmetry Index is as follows:

$$\text{Asymmetry Index} = \frac{\text{Area} \times \text{Trend Symmetry}}{\text{Length}}. \quad (1)$$

A smaller value of this index indicates a higher degree of symmetry in human walking.

D. Statistical Analysis

For the statistical analysis, continuous data were summarized using mean values, standard deviations (SD), root mean

TABLE I
COMPARISON OF CYCLOGRAM PARAMETERS AND PROPOSED ASYMMETRY INDEX ACROSS HIP, KNEE, AND ANKLE JOINTS IN FOUR DIFFERENT TASKS FOR A SAMPLE SUBJECT.

Joint	Cyclogram Parameter	Normal	Weight	Brace	Brace+Weight
Hip	Area	650.281	700.029	668.643	697.939
	Orientation	1.445	1.443	3.447	3.257
	Trend Symmetry	1.085	1.822	4.501	3.831
	Proposed Asymmetry Index	9.080	16.708	42.023	36.949
Knee	Area	1427.852	1332.003	1174.144	1338.099
	Orientation	0.037	0.416	3.305	4.324
	Trend Symmetry	1.0145	1.995	1.994	2.552
	Proposed Asymmetry Index	15.056	28.563	27.820	40.560
Ankle	Area	750.708	663.508	660.648	750.708
	Orientation	-6.210	-2.841	-4.285	-3.210
	Trend Symmetry	8.951	10.457	7.757	11.003
	Proposed Asymmetry Index	122.099	124.910	96.050	154.522

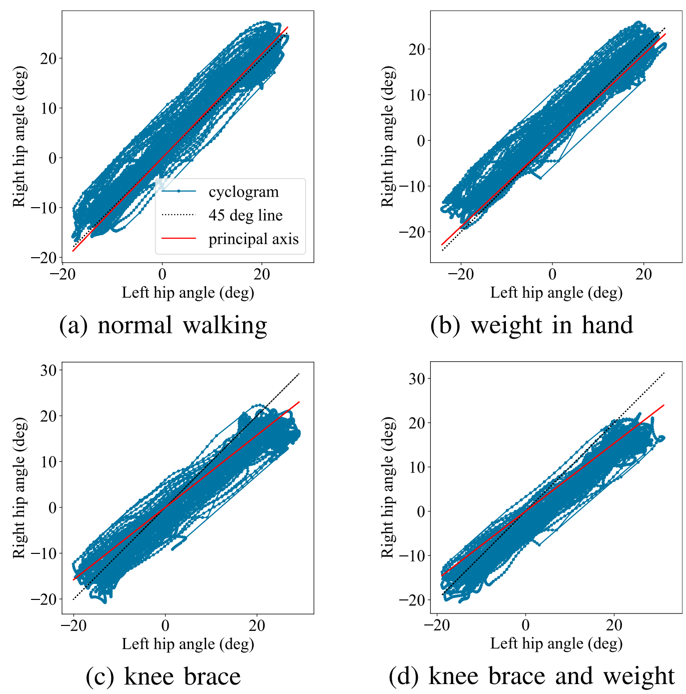
square (RMS), and standard error. The normality of the data was assessed using the Skewness and Kurtosis test as well as the Shapiro-Wilk test. When the data did not follow a normal distribution, comparisons were made using the Mann-Whitney U test. A p-value of less than 0.05 was considered statistically significant.

III. RESULTS AND DISCUSSION

This section presents the gait analysis outcomes, focusing on the symmetry index under different conditions: normal walking, walking with a knee brace on the dominant leg, and walking while holding a weight in the dominant hand. Various features were extracted from the cyclogram diagrams to assess asymmetry in walking. Table I summarizes parameters such as area, orientation, trend symmetry, and the proposed asymmetry index for a sample subject.

The results reveal distinct asymmetry patterns across the hip, knee, and ankle joints under different walking conditions. The hip joint exhibited a relatively stable area parameter across all tasks, with the proposed asymmetry index increasing notably when a knee brace was applied, and when combined with a weight in hand. This suggests that the hip joint is sensitive to external disturbances, reflecting changes in gait symmetry. In contrast, the knee joint showed more pronounced changes in the area and orientation parameters, particularly under the brace and weight conditions, indicating a higher susceptibility to these factors. The ankle joint, however, displayed significant variability in the trend symmetry and proposed asymmetry index, suggesting that the ankle may contribute more to compensatory adjustments during asymmetric gait. As a result, the hip joint's consistent response to changes in walking conditions underscores its importance in assessing gait asymmetry, potentially offering a more reliable indicator of asymmetry compared to the knee and ankle joints. In further analysis, the hip angle is considered for detecting asymmetry.

Fig. 5 presents cyclogram diagrams for the hip angle across different walking tasks for a sample subject. The black dashed line represents the 45-degree line, indicating perfect symmetry between left and right hip angles, while the red line is the principal axis fitted to the cyclogram shape. The alignment between these lines is close together in normal walking, indicating symmetric hip movements. When holding weight, a slight deviation appears, suggesting minor asymmetry. However, in the conditions involving the knee brace and the combination of both the knee brace and weight, the misalignment between the lines becomes more pronounced, indicating increased asymmetry. These results suggest that external factors like the knee brace and weight significantly disrupt the symmetry of hip movements, with the brace having a more substantial impact on gait asymmetry, particularly when combined with additional weight.



(a) normal walking (b) weight in hand
(c) knee brace (d) knee brace and weight

Fig. 5. A sample illustration of cyclogram diagrams for hip angle for a sample subject across four conditions: normal walking, walking with weight in hand, walking with a knee brace, and walking with both a knee brace and weight in hand.

The box plot in Fig. 6 provides a clear visualization of the proposed asymmetry index across different walking conditions. The median values for each condition are shown within the boxes, allowing for a straightforward comparison

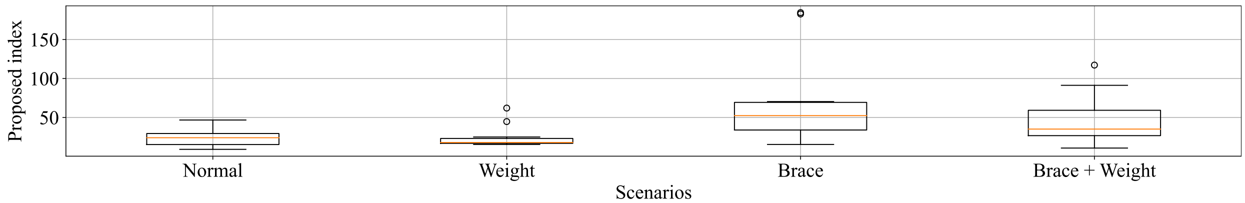


Fig. 6. Box plot representation of proposed asymmetry index for hip angle under four different walking conditions.

TABLE II
DESCRIPTIVE STATISTICS FOR TREND SYMMETRY AND PROPOSED ASYMMETRY INDEX FOR HIP ANGLE

	Trend Symmetry				**Proposed Asymmetry Index**			
	Normal	Weight	Brace	Brace+Weight	Normal	Weight	Brace	Brace+Weight
RMS	3.045	3.111	8.411	5.826	25.862	28.554	89.338	56.233
Standard error	0.355	0.396	1.566	0.966	3.321	4.499	17.991	9.864
Mean	2.830	2.847	6.798	4.959	23.633	24.757	68.881	46.788
Standard deviation	1.179	1.314	5.194	3.206	11.016	14.922	59.668	32.715

TABLE III
RESULTS OF THE MANN-WHITNEY U-TEST COMPARING THE WALKING CONDITIONS

Comparison	***p*-value**
Normal vs Weight	0.646
Normal vs Brace	0.013
Normal vs Brace+Weight	0.042
Weight vs Brace	0.036
Weight vs Brace+Weight	0.049
Brace vs Brace+Weight	0.393

of central tendencies. The interquartile ranges (IQRs) indicate the variability in the data, with wider boxes suggesting more variability in asymmetry measures. Whiskers extend to show the range of the data, and any outliers are marked beyond these whiskers, highlighting data points that deviate from the general trend. Notably, the box plots reveal a shift in the median values when comparing normal walking to the knee brace condition, suggesting increased asymmetry with the knee brace. The relatively smaller spread in the weight condition indicates less variability, supporting the conclusion that holding weight minimally impacts walking symmetry.

The descriptive statistics in Table II highlight the comparative analysis of trend symmetry and the proposed asymmetry index for hip angles under four walking conditions for all participants. The trend symmetry metric shows relatively low values across all conditions, with a notable increase under the knee brace and knee brace with weight conditions, indicating greater asymmetry in these scenarios. The proposed asymmetry index, which integrates additional factors like cyclogram area and the longest length of the cyclogram, exhibits a more pronounced differentiation between the conditions. Specifically, while the mean and RMS values of the proposed asymmetry index are modest in the normal and weight conditions, they significantly escalate in the knee brace and knee brace with weight conditions, suggesting a higher sensitivity to changes in gait symmetry.

The results presented in Table III summarize the p-values from the Mann-Whitney U-test comparing different walking conditions. The comparison between normal walking and holding a weight shows no significant difference, suggesting that carrying a weight does not notably affect gait asymmetry. However, significant differences are observed when comparing normal walking with wearing a knee brace, as well as normal walking with both a knee brace and weight, indicating that the brace has a considerable effect on gait symmetry. Similarly, the weight vs. brace and weight vs. brace and weight comparisons also show significant differences, reinforcing the impact of the brace on asymmetry. In contrast, the comparison between the brace and brace and weight conditions reveals no significant difference, implying that adding weight does not further alter the asymmetry introduced by the brace alone.

These findings align with the study's goal of developing a comprehensive asymmetry index that can effectively differentiate between various gait conditions, offering valuable insights for biomechanics assessments, interventions, and developing bipedal walking robots.

While the proposed asymmetry index provides promising insights, certain limitations must be acknowledged. The study involved a limited number of subjects, all of whom were healthy individuals. Including patients in future research could yield more clinically applicable and valid results. Additionally, the study focused on a narrow range of weights; exploring a broader range may offer deeper insights into the relationship between weight and asymmetry. Finally, the index was evaluated solely under normal walking conditions, and its performance under fast walking conditions remains to be assessed.

IV. CONCLUSION

This study introduced a gait asymmetry index derived from cyclogram analysis using image processing techniques. The purpose was to provide a more detailed assessment of lower limb movements under various walking conditions by integrating parameters such as cyclogram area, trend symmetry, and the longest length of the cyclogram shape. The findings highlight that the proposed asymmetry index is sensitive enough to detect changes in gait symmetry caused by wearing a knee brace, with the hip joint proving to be the most informative in identifying these asymmetries. The introduced index was validated through statistical analysis, demonstrating its potential as a valuable tool for diagnosing and monitoring gait-related conditions. This research contributes to a deeper understanding of gait asymmetry by employing image processing to analyze cyclograms. The findings improve biomechanical assessments and rehabilitation strategies for human gait, and they also potentially provide insights for developing and optimizing bipedal walking robots, ensuring more accurate and efficient movement patterns under various walking conditions. As for future work, the suggested analyses can be applied explicitly to robotics to evaluate its potential in the field of walking robots.

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