

Wearable Sensor Based Gait Asymmetry Visualization Tool

Completed Research

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Abstract

Real time visualization of gait asymmetry can provide added value in rehabilitation, clinics and sports. Common approaches for the quantification of gait asymmetry give the numerical values of parameters such as symmetry index, symmetry ratio, symmetry angle etc. It may be difficult for users to understand those numerical values. In order to conveniently use quantitative gait asymmetry monitoring for users, an affordable visualization tool is useful to provide a facility for their use in clinic and at home. This paper investigates four approaches for monitoring gait asymmetry to provide automatic graphical visualizations of information about gait. The results show that affordable wearable Inertial Measurement Unit sensors can be used for objective gait asymmetry feature extraction without the requirement and expense of an elaborate laboratory setup. Our procedure significantly simplifies the monitoring protocols and opens possibilities for home based assessment and supports digital transformation strategies through the development of new technology.

Keywords

Gait Visualization, Gait Asymmetry, Gait Feature Extraction, Inertial Measurement Unit, Gait Analysis.

Introduction

Every individual's gait pattern is assumed to be symmetrical with right and left sides performing identical locomotion. In reality the limb movement of one side is not exactly repeated on the other side and in normal gait an arbitrary cut-off value of 10% deviation from perfect asymmetry has been used as a criterion of asymmetry (Patterson et al. 2010). However gait asymmetry is also an indicator of different diseases and disease progression and has also been shown to be a determinant of recovery in patients with various medical conditions such as stroke (Patterson et al. 2008) and Parkinson's disease (Plotnik et al. 2005). It has also been used to monitor patient progress in orthopaedics and rehabilitation (Steultjens et al. 2000). Gait asymmetry is important in older patient fall risk assessment (Yogev et al. 2007). It is also a predictor of functional and cognitive decline (Plotnik et al. 2011) and results in a reduced quality of life. Gait asymmetry has therefore attracted the interest of researchers in various disciplines and its measurement is of importance. The tools and methodologies used are often studied in artificial controlled conditions such gait laboratories which are not widely available and expensive to use routinely. In current clinical practice, human visual observation is mostly used to identify gait asymmetry. Such crude methods are subjective and not convenient for ordinary users (Archer et al. 2006).

Related Works

The tools and methodologies used to assess human gait are often arbitrary and often studied in artificial controlled conditions. Gait abnormalities are generally assessed and reported by physicians, physiotherapists and researchers in clinical settings or in gait laboratories. Clinical scales used to analyse gait parameters are subjective or semi-subjective and a poor replacement to laboratory based methods for identifying changes in gait asymmetry. Different assessment tools such as the Gait Abnormality Rating Scale (Brach and VanSwearingen 2002), Figure of 8 Walk Test (Hess et al. 2010), and Berg Balance Scale (Berg et al. 1992), are used to observe a patient's gait and balance. These are mostly based on visual observation, sometime provide scoring based on clinical expertise and sometime abnormality reported as present or not. Such reports may not satisfy scientific criteria of reliability and validity (Archer et al. 2006). The other available common approaches for gait quantification of temporal and spatial gait pattern are Symmetry index (SI) (Robinson et al. 1987), Symmetry ratio (Seliktar and Mizrahi 1986), Ratio (Vagenas and Hoshizaki 1992), Gait asymmetry (Plotnik et al. 2007), Symmetry angle and Symmetry indices (Hodt-Billington et al. 2011).

However, there are often difficulties in how to interpret results. The most commonly used SI approach needs to be normalized to a reference value (Błażkiewicz et al. 2014) and there is a potential influence for artificial inflation as the normal values for young and older subjects are not the same (Herzog et al. 1989). A mean value calculation used for quantifying gait asymmetry may also lead to erroneous results as the mean measurements from two abnormal limbs may appear normal. Another visual representation method of examining asymmetric behaviours is presented in (Manal and Stanhope 2004). Here movement pattern deviations are displayed relative to normative data by color-coding the magnitude and the direction of the deviation. This method however lacks quantitative information and does not examine changes in symmetry of bilateral parameters.

To address these considerations, we develop a simple, affordable and wearable multi-sensor based user friendly visualization tool of gait asymmetry information which is easy to result interpretation. Such a tool needs to be portable to make it usable in routine clinical practice including the patient's home. To date, an automatic real time gait asymmetry visualization technique based on affordable fused synchronous accelerometer and gyroscope data is not commercially available. The aim of this study is to visualize gait asymmetry based on accelerometer and gyroscope data to increase the reliability and validity of monitoring gait abnormalities using the automatic lower limb gait features extraction method proposed in (Anwary et al. 2018b). This can support digital transformation strategies through the development and use of new and affordable technologies for diagnosis and monitoring of gait that results in structural change in the delivery of healthcare that can be delivered in the patient's own home (Matt et al. 2015).

Methodology

We describe the materials and methods used for the development of this work in the following subsections.

Data collection

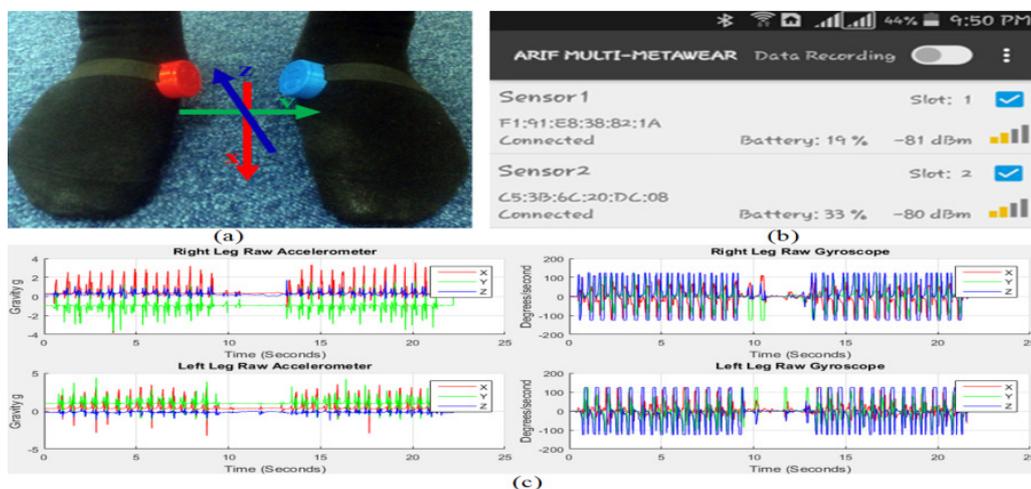


Figure 1. (a) IMU sensors placement in right and left metatarsal feet locations, (b) Android app for synchronous data collection, (c) Raw accelerometer and gyroscope data of young subject 1

Sensors are placed at metatarsal foot locations of both legs for collecting data since this can achieve the best performance (Anwary et al. 2018b). We design and develop an android app for synchronous data collection from accelerator and gyroscope. We recruited convenience sample of 20 subjects with 10 healthy young subjects (9 male, mean age 25.3 years, standard deviation 4.64, range 19-35 years), and 10 older subjects (9 male, mean age 69.4 years, standard deviation 7.28, range 62-86 years). Subjects perform a walk in a straight corridor comprising of 15 strides of normal forward walking, a turn-around and another 15 strides. Accelerometer and gyroscope data are collected by placing the sensors on right and left metatarsal foot locations of the barefoot. Accelerometer and gyroscope raw data for all the strides from young subject 1 is presented in Figure 1(c). Our method has been validated to pick up regular features occurring in the human gait cycle (stride) as shown in Figure 2a which show the salient features. Each stride contains stance and swing phases. A stride is the distance between a point on one foot, usually the heel, at the first foot contact and the same point on that foot at the next foot contact. It is made up of two steps. Figure 2a shows stance and swing phases of a gait cycle which consists eight events identifiable from our signal (Figure 2b) (Anwary et al. 2018b).

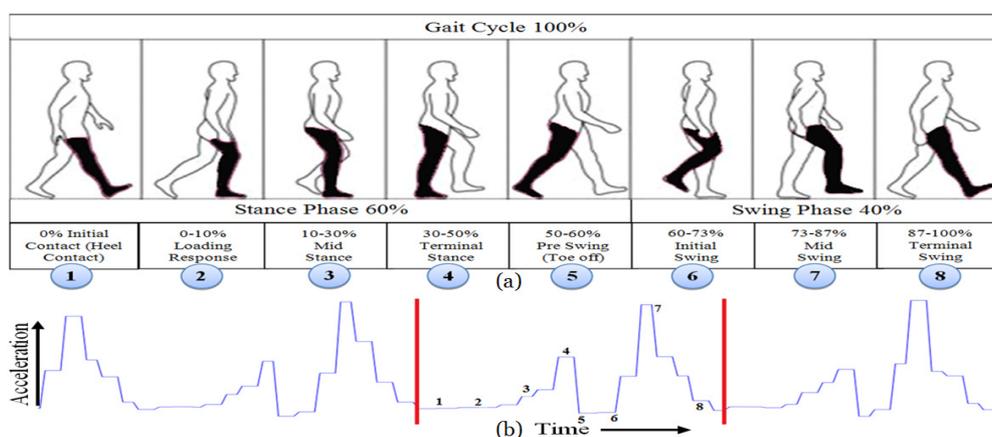


Figure 2. (a) Normal human gait phases, (b) Eight different phases of a gait cycle from accelerometer data (Anwary et al. 2018b)

Gait features extraction

Stride, stance, swing and step phase detection

We use the stride detection technique based on the local minimal prominence characteristics of strides associated with the time-varying magnitude of acceleration (Anwary et al. 2018a). This detected the foot’s initial contact to the ground (start of gait cycle), the end of the stance and the beginning of the swing phase and the end of swing and the start of the new gait cycle from both legs.

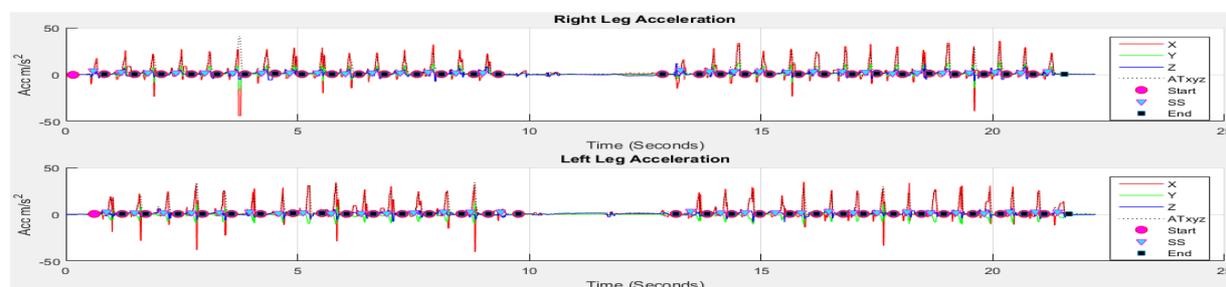


Figure 3. Result of stride, stance and swing event detection

Figure 3 shows detected event of the foot’s initial contact to the ground, *Start* (purple circle), the transition of stance-swing phase *SS* (cyan triangle) and the terminal swing *End* (black square) of gait event

information of each stride for both legs where the stance phase information is provided by the difference between *Start* and *SS*; and the swing information is the difference between *SS* and *End*.

Velocity and distance estimation

Trapezoidal double integral approach (Thong et al. 2004) is applied to obtain travelled distance from the user movement using accelerometer data. First integration retrieves the current velocity and then second integration computes velocity and calculates distance travelled. Input data are passed through a high-pass filter to remove the direct component of the acceleration signal. Our measurements of extracting features is validated with Qualysis Motion Capture System (Anwary et al. 2018b).

Data and statistical analysis

We obtain values for ten spatial-temporal gait parameters separately from the right and left lower limbs include stride length (m), stride time (s), stride velocity (m/s), step length (m), step time (s), step velocity (m/s), stance time (s), swing length (m), swing time (s) and swing velocity (m/s). Asymmetry factors SI (Robinson et al. 1987), SR (Seliktar and Mizrahi 1986), Ia (Vagenas and Hoshizaki 1992), GA (Plotnik et al. 2007) and SA (Zifchock et al. 2008) are calculated for each parameter using equations (1) to (5). These are chosen because they are very commonly used approaches of evaluating gait asymmetry (Patterson et al. 2010).

$$SL1 - SI \text{ (Robinson et al. 1987):} \quad SI(\%) = \frac{RightLeg - LeftLeg}{0.5(RightLeg + LeftLeg)} * 100 \quad (1)$$

$$SL2 - SR \text{ (Seliktar and Mizrahi 1986):} \quad SR(\%) = \frac{RightLeg}{LeftLeg} * 100 \quad (2)$$

$$SL3 - Ia \text{ (Vagenas and Hoshizaki 1992):} \quad Ia(\%) = \frac{RighttLeg - LefttLeg}{\max(RightLeg, LeftLeg)} * 100 \quad (3)$$

$$SL4 - GA \text{ (Plotnik et al. 2005):} \quad GA = \left| \ln \left\{ \frac{\min(RightLeg, LeftLeg)}{\min(RightLeg, LeftLeg)} \right\} \right| \quad (4)$$

$$SL5 - SA \text{ (Zifchock et al. 2008):} \quad SA(\%) = \frac{(45^\circ - \arctan(RightLeg / LeftLeg))}{90^\circ} * 100\% \quad (5)$$

SL1 is based on percentage assessment of difference between kinematic and kinetic parameters for both legs during walking. SI=0 indicates that there is no asymmetry and SI ≥ 100% indicates high asymmetry. SL2 indicates the highest value results asymmetries. SR=100 indicates no asymmetry, SR > 100 indicates right leg value is higher than left leg and SR<100 indicates that left leg value is higher. SL3 is based on kinematic asymmetry of the lower limbs. Ia=0 indicates no asymmetry. Ia = ±0, the higher the value indicates the higher level of asymmetry. SL4 is based on logarithmic transformation of right and left leg's ratio of gait asymmetry. GA=0 and GA=1 denote no asymmetry and highest asymmetry respectively. SL5 is the symmetry angle calculated for the angle of the vector plotted from the right and left values of discrete gait parameters. SA shows absolute value of right and left leg's ratio in percentage. SA=0 indicates no asymmetry and SA≥100% indicates asymmetry.

Experimental data are compared to normal distribution using Shapiro Wilk test. Pearson's linear correlation coefficients are calculated. Correlation between experimental results and linear least square regression is analyzed. Although available asymmetry factors SI (Robinson et al. 1987), SR (Seliktar and Mizrahi 1986), Ia (Vagenas and Hoshizaki 1992), GA (Plotnik et al. 2007) and SA (Zifchock et al. 2008) provide a numerical indication of the degree of asymmetry they are not easily interpretable to users. These rely on the computation of complex equations as well as knowledge to interpret the results. This may affect the accuracy of use. Therefore, in order to conveniently use quantitative gait asymmetry monitoring, an easy to interpret and affordable gait symmetry visualization tool is required to provide a facility for use in clinic and at home. This paper mainly presents the gait asymmetry visualization to the users, not give the cause of gait asymmetry. Cause of gait asymmetry is an important topic to conduct research in future.

Visualization of gait asymmetry

We purposely show the visualizations from a single subject as there is no point in showing an aggregate of results from our 20 subjects. Individual visualizations for all are estimated. This section presents four novel gait asymmetry visualization approaches aimed to show the various aspects of gait symmetry analysis and make the results accessible and useful to both patients, for self-directed care, and therapists: **1) Real time dial visualization:** this is intended for patient use by providing a spatiotemporal gait information to the patient who can then identify and make attempts to rectify gait asymmetry; **2) Visualization of individual leg time variation:** this is intended for therapists assessing gait by giving an overall picture of time asymmetry over a series of strides. In normal human gait the period from the initial contact to pre-swing composes about 60% of the time and initial swing and terminal swing composes about 40% of the time in the gait cycle shown in Figure 2a. This visualisation provides therapists the opportunity easily identifies any deviation from this 60:40 split; **3) Visualization of both legs asymmetry:** this visualization shows both time and distance for stride and step for both legs. As they are comparing both legs then they would be expected to be as near to equal as possible and any difference is asymmetry; This will also indicate which of the legs is most affected and helps therapists direct attention to the legs with most abnormality; and **4) Boxplot-based visualization:** this visualization provides an overall summary of the results obtained through the above and therefore can be used to monitor progress with therapy.

1) Real time dial visualization

Stride, step and swing information is considered for visualization. We extract stride, stance, swing and step features. Stance is a stationary phase of a gait cycle and distance travelled in the stationary phase is zero. Initially we estimate the maximum (max), minimum (min), and confidence interval (CI) of each feature. We draw a circle from $\theta=0$ to 2π of duration of 0.01 using $x = \sin(\theta)$, $y = \cos(\theta)$. We define the interval $\alpha=50$ and value of each step increment (δ) is computed by $\delta = (max - min) / \alpha$. Interval angle ω is estimated using $\omega = \lambda * \pi / \alpha$ with $\lambda = 1.25$. Scale is represented from 0 to α using $\gamma = -\lambda * \pi / i * n + \lambda * \pi$, for $n=0$ to α .

The small scale line is then drawn using $x = \sin(\gamma)$, $y = \cos(\gamma)$. Minimum and maximum values of the scale are the lower CI and upper CI respectively. Indicator line (β) is then set with the instantaneous difference between left and right value of the feature (η) using $\beta = -\omega * (\eta - min) / \delta + \lambda * \pi$. The indicator line is drawn from 0 to β . We draw gradient colors to make it colorful looking. Instantaneous feature value is displayed at the bottom of each dial with seven segment display. The same procedure is followed for displaying instantaneous distance and time from stride, step and swing information.

When the app is run for the first time, there is an option to input a number of last performed strides. By default, the value is set as 30. It will then detect phases and display corresponding information on to dial. Every time it starts, it will restore the last calculated CI for scaling and it will update automatically after each 30 or specified numbers of strides. There is an option to change the scaling factor according to SI (Robinson et al. 1987), SR (Seliktar and Mizrahi 1986), Ia (Vagenas and Hoshizaki 1992), GA (Plotnik et al. 2007) and SA (Zifchock et al. 2008) format.

2) Visualization of individual leg time variation

Each stride is composed of stance and swing phases. Stride time is composed of stance time and swing time. To visualize the individual legs variation, we estimate the maximum and minimum values of each feature. We draw an outline rectangle using blue color towards vertical line to represent right of the first stride value with aspect ratio of the maximum value. A cyan color rectangle of stance time is drawn on that stride rectangle and a yellow color rectangle of swing time is drawn at the top of the stance rectangle. All rectangles are followed the aspect ratio with the maximum value. This process is conducted for all stored strides.

3) Visualization of both legs asymmetry

Each stride and step feature has distance and time information. Initially we calculate the maximum and minimum of features. A red color rectangle is drawn which height is the first right stride distance with aspect ratio of the maximum value. A blue rectangle is drawn which height is the left stride distance at the side of right rectangle. We follow this procedure for both strides and step asymmetry visualization of all stored strides considering the aspect ratio with the maximum value.

4) Boxplot-based visualization

We estimate median, upper-quartile, lower quartile and whisker values from features and plot a Boxplot. This is a simple representation of descriptive statistics to understand each features distribution, non-normal/unusual level, outliers, symmetry and overall gait asymmetry information.

Results

Preliminary experimental results from a subject: We extract automatic gait asymmetry features based on accelerometer and gyroscope data collected from both feet.

Gait asymmetry features information

The total time taken to travel 33.38 meters is 22.21 seconds. The estimated legs travelled distances are 33.35 meters and 32.87 meters with accuracy of 99.92% and 98.48%. Actual and estimated distances are very close. Accuracy of stride and step event detection is 100%. Table 1 shows the average gait variability and quantifying gait asymmetry using five techniques.

Gait Features	Right Leg		Left Leg		SL1	SL2	SL3	SL4	SL5
	Mean	95% CI	Mean	95% CI	SI	SR	Ia	GA	SA
Stride Length (m)	1.112	0.225	1.096	0.230	1.45	101.46	-1.44	0.01	0.46
Stride Time (s)	0.595	0.027	0.588	0.026	1.13	101.13	-1.12	0.01	0.36
Stride Velocity (m/s)	1.823	0.308	1.855	0.371	-1.73	98.29	1.71	0.02	-0.55
Step length (m)	0.507	0.041	0.387	0.043	26.68	130.79	-23.54	0.27	8.44
Step time(s)	0.258	0.028	0.337	0.027	-26.58	76.53	23.47	0.27	-8.41
Step Velocity (m/s)	2.185	0.337	1.256	0.223	53.98	173.94	-42.51	0.55	16.78
Stance Time (s)	0.315	0.018	0.278	0.021	12.36	113.17	-11.64	0.12	3.93
Swing Length (m)	1.009	0.202	0.990	0.207	1.88	101.90	-1.86	0.02	0.60
Swing Time (s)	0.280	0.019	0.310	0.021	-10.18	90.31	9.69	0.10	-3.24
Swing Velocity (m/s)	1.729	0.248	1.537	0.248	11.79	112.53	-11.13	0.12	3.75

Table 1: Gait variability and asymmetry factors (SI, SR, Ia, GA and SA)

Table 1 shows that the mean stride lengths and times of both legs are very close. However, high asymmetry is found in step length, time and velocity. Estimated asymmetry factors show numerical values that indicate differences both between the features and between the indicators. The lowest gait asymmetry is observed during the stride phase and the highest is found during the step event. Using the Shapiro-Wilk test, most of the parameters show normal distribution for 20 participants. Additionally, the lowest confidence intervals are observed for most of the parameters indicating consistent data.

Analysis of Pearson linear correlation coefficients between SL1, SL2, SL3, SL4 and SL5 factors indicates a very strong association ($p < 0.001$) for most of the cases excluding SL4. As such, it is more useful to analyze the compatibility of the results for individual factors in the assessment of the symmetry of the factors indicating high symmetry. Coefficient ordered rank also agrees for most of the cases. The linear least square regressions show very high correlations. It is important for clinical practice to evaluate the impact of individual factors resulting high gait symmetry and the interpretation of these numerical values provide limited information. Therefore, a visual representation of these values with interpretation would provide much more user friendly information.

Gait asymmetry visualization

Next, we show the results of the four gait asymmetry visualizations.

1) Real time dial visualization

Figure 4 demonstrates spatiotemporal measurements in a dial fashion taken from one subject. Both legs should theoretically give identical results and therefore perfect asymmetry should give dial indicator readings of zero. The first dial is an asymmetry display for stride length and time comparing both legs. The second dial displays the real time measurement of step length and time. It is noted that there is a difference in the level of asymmetry. The third dial shows the swing phase distance and time. Similarly, there is little asymmetry between two legs. The scales on all three dials represent the confidence intervals and the pointer

represents the instantaneous real time difference between two legs. For example, in this case although the dials for stride and swing show near perfect symmetry, measurements relating to step are not. Step measurement entails information on distance and time. The distance dial shows that right leg is travelling longer (0.51m) than left leg (0.39m). The patient therefore needs to shorten the distance travelled by the right leg and/or make the left step longer. Time dial demonstrates the right leg travels the longer distance in a shorter time (0.26s) compared to the left leg (0.34s). Digital number below the dial is showing the absolute measure for all three markers.

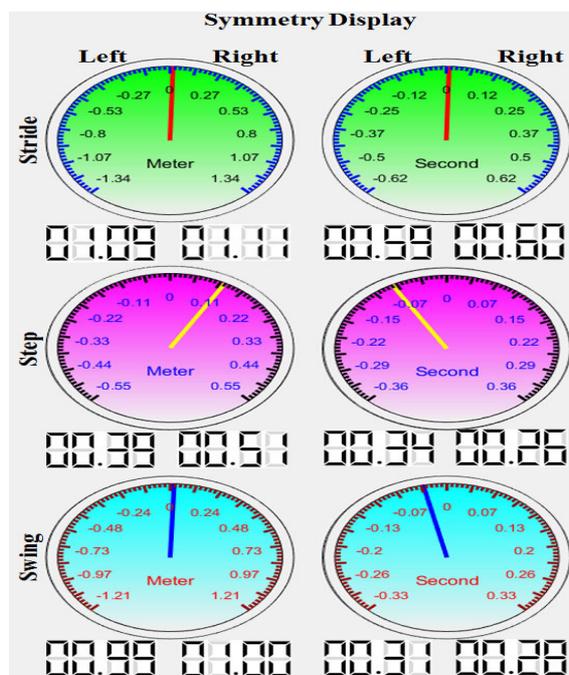


Figure 4. Real time gait asymmetry visualization

2) Visualization of individual leg time variation

30 strides are performed and time of stride, stance and swing phases is presented in Figure 5 where each bar shows the stride time.

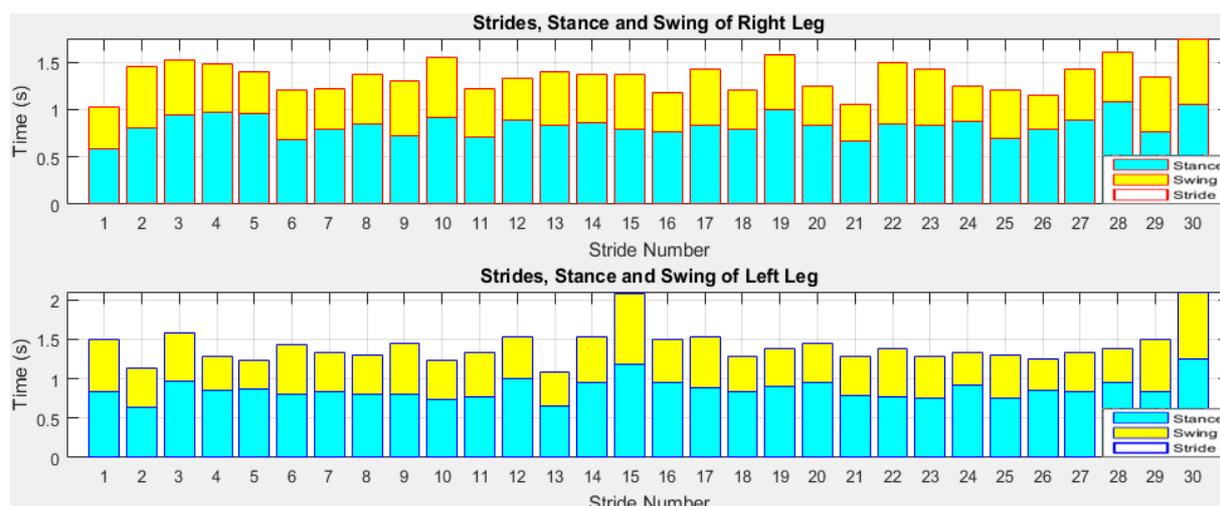


Figure 5. Time of stride, stance and swing phases from right and left legs

Cyan and yellow colors represent the time of stance and swing phases respectively. There is a small variation of stance and swing phase timing. This visualization clearly represents the variability of stance and swing

phases in each stride of the legs. The ratio of stance and swing is found closest to the 60:40% split for average stride, stance and swing information (Figure 5).

3) Visualization of both legs asymmetry

In this visualization the stride and step asymmetry information for both time and distance from both legs are presented in Figure 6. We observe that while there is good symmetry in the stride there is strong variation in the step phases.

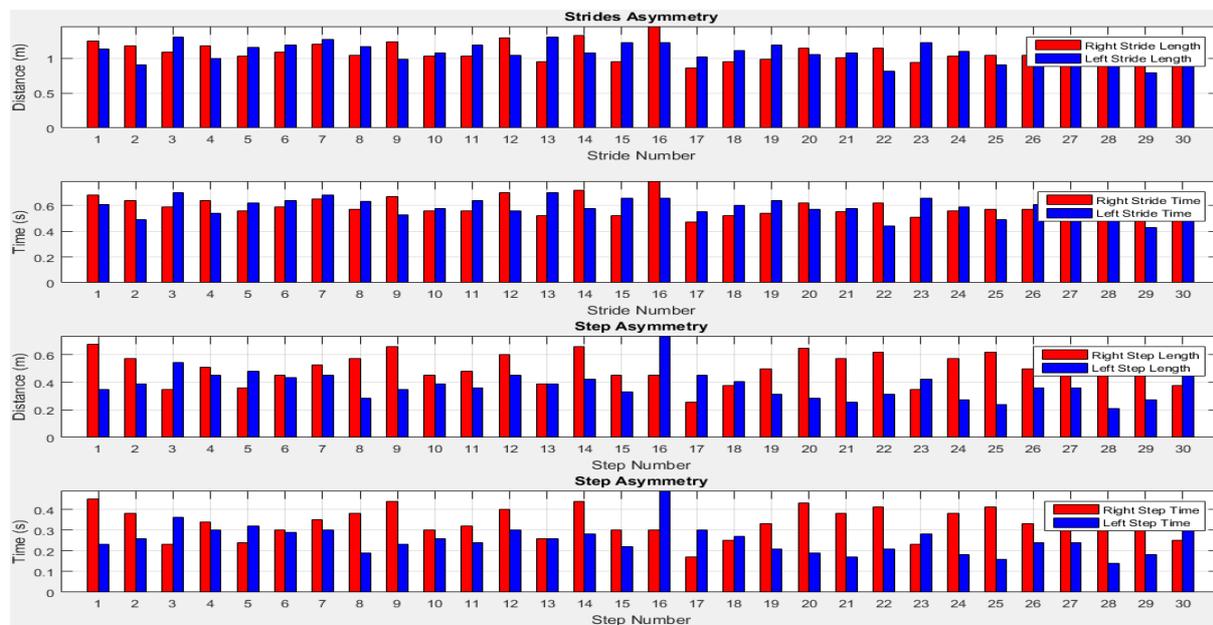


Figure 6. Gait asymmetry of stride and step phases from right and left legs

4) Boxplot-based visualization

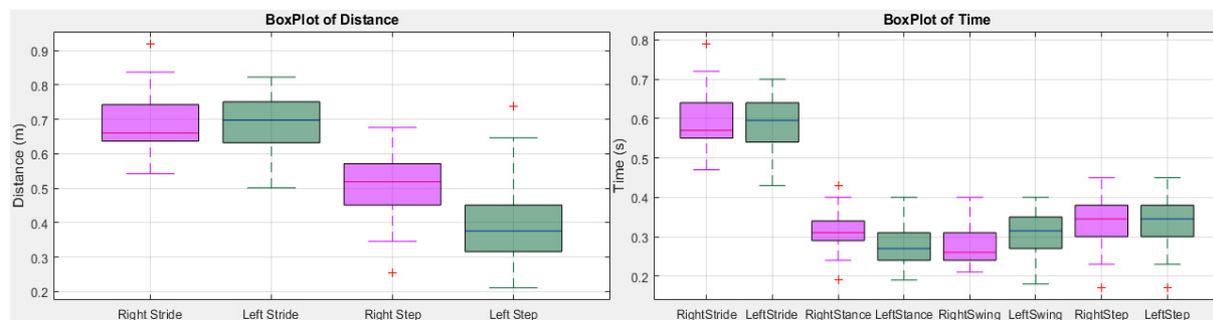


Figure 7. Boxplot of stride, stance and swing information

Figure 7 shows a boxplot of the distribution of values for individual factors where the mean values obtained for stride and step for both legs. The quartile ranges are identified in the boxplot and show low variation for the stride. First box plot shows higher variation in the step length on the left leg than on the right. This demonstrates that although the stride length is similar on the right and left there can be a higher variation in the step length. Boxplots for time indicate that variation is low for both legs. If we exclude the first and last stride of each walking on the corridor, the asymmetry is not that high. Those phases consist of more variation due to initial acceleration and ending momentum. It is noted that the observations identified by the boxplots are not especially extreme.

Conclusion

In biometrics and biomedical engineering, gait analysis has been used to characterize human locomotion and has many applications (Bora et al. 2015). This paper presented four gait asymmetry visualization approaches: 1) Real time dial visualization; 2) Visualization of individual leg time variation; 3) Visualization of both legs asymmetry; and 4) Boxplot-based visualization. Real time dial visualization showed the instantaneous gait asymmetry of both legs from distance and time of stride, step and swing phases of each gait cycle using a dial and an indicator. It also showed instantaneous distance and time of stride, step and swing values in a seven segment display. Individual leg variation visualization showed the variation in stride, stance and swing phases in time. Both legs asymmetry visualization showed the asymmetry between two legs for strides and steps. Boxplot-based visualization showed the overall stride, step, stance and swing phases distribution. These methods are user friendly and easy to interpret and have the potential of helping professionals detect and interpret gait asymmetry.

This study adds to current literature by demonstrating a new visual method of demonstrating gait asymmetry that increases the reliability and validity of monitoring gait abnormalities. In addition, our sensors are wearable and can be used in different clinical setting and the patient's home and do not rely on complex equipment. This has the potential of a significant advance. As, gait asymmetry has been shown to be a determinant of recovery in patients suffering from several conditions with stroke (Hodt-Billington et al. 2008), lower limb amputations (Skinner and Effeney 1985), osteoarthritis (Shakoor et al. 2003) and cerebral palsy (Winiarski) such equipment may have a role in the evaluation of such patients. It can also be used to monitor patient progress in orthopedics and rehabilitation (Steultjens et al. 2000). There is also a potential use in sports training where running as close as possible to zero asymmetry may improve an athlete's performance (Wahab and Bakar 2011).

Our proposed real time dial based visualization tools offer an easy and user friendly way to visualize and monitor gait asymmetry. Therefore, our proposed gait information visualization approaches can be used for different applications at home as well as in clinics for gait monitoring and rehabilitation. This has the potential of making gait asymmetry analysis more widely available for use.

Ethical approval

Ethical approval for this research was granted by the Bournemouth University ethical review committee and each subject was given a Participant Information Sheet and signed an informed Participant Agreement Form.

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References and Citations

- Anwary, A., Yu, H., and Vassallo, M. 2018a. "An Automatic Gait Feature Extraction Method for Identifying Gait Asymmetry Using Wearable Sensors," *Sensors* (18:2), p. 676.
- Anwary, A.R., Yu, H., and Vassallo, M. 2018b. "Optimal Foot Location for Placing Wearable Imu Sensors and Automatic Feature Extraction for Gait Analysis," *IEEE Sensors Journal* (18:6), pp. 2555-2567.
- Archer, K.R., Castillo, R.C., MacKenzie, E.J., and Bosse, M.J. 2006. "Gait Symmetry and Walking Speed Analysis Following Lower-Extremity Trauma," *Physical therapy* (86:12), p. 1630.
- Berg, K.O., Wood-Dauphinee, S.L., Williams, J.I., and Maki, B. 1992. "Measuring Balance in the Elderly: Validation of an Instrument," *Can J Public Health* (83:2), Jul-Aug, pp. 7-11.
- Błażkiewicz, M., Wiszomirska, I., and Wit, A. 2014. "Comparison of Four Methods of Calculating the Symmetry of Spatial-Temporal Parameters of Gait," *Acta of bioengineering and biomechanics* (16:1), pp. 29-35.
- Bora, N.M., Molke, G.V., and Munot, H.R. 2015. "Understanding Human Gait: A Survey of Traits for Biometrics and Biomedical Applications," *2015 International Conference on Energy Systems and Applications*, pp. 723-728.

- Brach, J.S., and VanSwearingen, J.M. 2002. "Physical Impairment and Disability: Relationship to Performance of Activities of Daily Living in Community-Dwelling Older Men," *Physical Therapy* (82:8), 2002-08-01 00:00:00, pp. 752-761.
- Herzog, W., Nigg, B.M., Read, L.J., and Olsson, E. 1989. "Asymmetries in Ground Reaction Force Patterns in Normal Human Gait," *Med Sci Sports Exere* (21:1), pp. 110-114.
- Hess, R.J., Brach, J.S., Piva, S.R., and VanSwearingen, J.M. 2010. "Walking Skill Can Be Assessed in Older Adults: Validity of the Figure-of-8 Walk Test," *Physical Therapy* (90:1), 21/04/2010 received 06/09/2010 accepted, pp. 89-99.
- Hodt-Billington, C., Helbostad, J.L., and Moe-Nilssen, R. 2008. "Should Trunk Movement or Footfall Parameters Quantify Gait Asymmetry in Chronic Stroke Patients?," *Gait Posture* (27:4), May, pp. 552-558.
- Hodt-Billington, C., Helbostad, J.L., Vervaat, W., Rognsvag, T., and Moe-Nilssen, R. 2011. "Changes in Gait Symmetry, Gait Velocity and Self-Reported Function Following Total Hip Replacement," *J Rehabil Med* (43:9), Sep, pp. 787-793.
- Manal, K., and Stanhope, S.J. 2004. "A Novel Method for Displaying Gait and Clinical Movement Analysis Data," *Gait & Posture* (20:2), 2004/10/01/, pp. 222-226.
- Matt, C., Hess, T., and Benlian, A. 2015. "Digital Transformation Strategies," *Business & Information Systems Engineering* (57:5), pp. 339-343.
- Patterson, K.K., Gage, W.H., Brooks, D., Black, S.E., and McIlroy, W.E. 2010. "Evaluation of Gait Symmetry after Stroke: A Comparison of Current Methods and Recommendations for Standardization," *Gait & posture* (31:2), pp. 241-246.
- Patterson, K.K., Parafianowicz, I., Danells, C.J., Closson, V., Verrier, M.C., Staines, W.R., Black, S.E., and McIlroy, W.E. 2008. "Gait Asymmetry in Community-Ambulating Stroke Survivors," *Archives of Physical Medicine and Rehabilitation* (89:2), pp. 304-310.
- Plotnik, M., Dagan, Y., Gurevich, T., Giladi, N., and Hausdorff, J.M. 2011. "Effects of Cognitive Function on Gait and Dual Tasking Abilities in Patients with Parkinson's Disease Suffering from Motor Response Fluctuations," *Experimental Brain Research* (208:2), pp. 169-179.
- Plotnik, M., Giladi, N., Balash, Y., Peretz, C., and Hausdorff, J.M. 2005. "Is Freezing of Gait in Parkinson's Disease Related to Asymmetric Motor Function?," *Annals of Neurology* (57:5), pp. 656-663.
- Plotnik, M., Giladi, N., and Hausdorff, J.M. 2007. "A New Measure for Quantifying the Bilateral Coordination of Human Gait: Effects of Aging and Parkinson's Disease," *Experimental brain research* (181:4), pp. 561-570.
- Robinson, R., Herzog, W., and Nigg, B. 1987. "Use of Force Platform Variables to Quantify the Effects of Chiropractic Manipulation on Gait Symmetry," *Journal of manipulative and physiological therapeutics* (10:4), pp. 172-176.
- Seliktar, R., and Mizrahi, J. 1986. "Some Gait Characteristics of Below-Knee Amputees and Their Reflection on the Ground Reaction Forces," *Eng Med* (15:1), Jan, pp. 27-34.
- Shakoor, N., Hurwitz, D.E., Block, J.A., Shott, S., and Case, J.P. 2003. "Asymmetric Knee Loading in Advanced Unilateral Hip Osteoarthritis," *Arthritis Rheum* (48:6), Jun, pp. 1556-15561.
- Skinner, H.B., and Effeney, D.J. 1985. "Gait Analysis in Amputees," *American journal of physical medicine* (64:2), Apr, pp. 82-89.
- Steultjens, M.P.M., Dekker, J., Baar, M.E.v., Oostendorp, R.A.B., and Bijlsma, J.W.J. 2000. "Range of Joint Motion and Disability in Patients with Osteoarthritis of the Knee or Hip," *Rheumatology* (39:9), 2000-09-01, pp. 955-961.
- Thong, Y.K., Woolfson, M.S., Crowe, J.A., Hayes-Gill, B.R., and Jones, D.A. 2004. "Numerical Double Integration of Acceleration Measurements in Noise," *Measurement* (36:1), pp. 73-92.
- Vagenas, G., and Hoshizaki, B. 1992. "A Multivariable Analysis of Lower Extremity Kinematic Asymmetry in Running," *International Journal of Sport Biomechanics* (8:1), pp. 11-29.
- Wahab, Y., and Bakar, N.A. 2011. "Gait Analysis Measurement for Sport Application Based on Ultrasonic System," *Consumer Electronics (ISCE), 2011 IEEE 15th International Symposium on*, pp. 20-24.
- Winiarski, S. "Are There Asymmetry Indices Reliable Indicator of Gait Performance?," *Gait & Posture* (30), pp. S143-S144.
- Yogev, G., Plotnik, M., Peretz, C., Giladi, N., and Hausdorff, J.M. 2007. "Gait Asymmetry in Patients with Parkinson's Disease and Elderly Fallers: When Does the Bilateral Coordination of Gait Require Attention?," *Experimental Brain Research* (177:3), pp. 336-346.
- Zifchock, R.A., Davis, I., Higginson, J., and Royer, T. 2008. "The Symmetry Angle: A Novel, Robust Method of Quantifying Asymmetry," *Gait & posture* (27:4), pp. 622-627.