POLISH ANNALS OF MEDICINE 24 (2017) 148–152

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: http://www.elsevier.com/locate/poamed

POLISH ANNALS OF MEDICINE

Original research article

Mathematical models in the evaluation of weight distribution asymmetry in lower limbs: Implication for practice

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ARTICLE INFO

Article history:
Received 27 April 2016
Received in revised form
25 June 2016
Accepted 16 August 2016
Available online 10 November 2016

Keywords:
Asymmetry
Limb loading
Mathematical model
Index
Ratio

ABSTRACT

Introduction: Mathematical models quantify asymmetry in weight distribution on bilateral lower limbs using indexes or ratios.
Aim: This study investigates the efficacy of mathematical models to evaluate weight distribution asymmetry in healthy and different clinical populations.
Material and methods: This cross-sectional study recruited 188 participants (149 healthy, 27 stroke and 12 unilateral total knee replacement) through convenience sampling for this study. Two digital weighing scales were used to capture the loading on bilateral lower limbs. The data is further computed with different mathematical models.
Results and discussion: The symmetry index model has problems of inflation with increasing asymmetry values. Symmetry ratio model exhibits low sensitivity to differences in weight distribution, and did not provide the magnitude and direction of absolute weight distribution asymmetry. The direction of the asymmetry is not meaningful from the symmetry angle model, and it fails to predict factual asymmetry values.
Conclusions: Modified symmetry index has better sensitivity to differences in bilateral lower limb weight distribution and is able to quantify the extent of asymmetries and identifies the side of asymmetry. Based on the study results, we suggest the application of the mathematical models to quantify limb loading in the following order: modified symmetry index, symmetry index, symmetry angle, and symmetry ratio for clinical or research practice.

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http://dx.doi.org/10.1016/j.poamed.2016.08.001
1230-8013/

1. Introduction

In quiet standing, when the body weight is distributed equally on bilateral lower limbs, the weight bearing is said to be symmetrical.[1] In clinical practice, achieving symmetrical weight bearing on the bilateral lower limb is a primary goal in neurological and orthopedic conditions such as stroke, joint replacement and amputees.[1–4] In the aforementioned conditions, the amount of weight distribution (WD) on the lower extremity is crucial in the process of recovery.[5] Asymmetrical weight bearing or non-weight bearing on the lower extremities on different stages of injury and postoperative rehabilitation could lead to a poor functional outcome.[1,3] Hence, evaluation of weight bearing on lower extremities is essential in clinical practice. Evaluation of symmetry of weight bearing between two lower extremities is carried through subjective clinical examination, as well as objectively through measurement devices.[5] Force platform, MatScan, Nintendo Wii balance board, and digital weighing scales are devices that provide more reliable and accurate weight bearing measurements.[6] The measurement data obtained from the devices are further computed using mathematical models to interpret the pattern (magnitude and direction) of asymmetry in WD on bilateral lower limbs.[7]

Mathematical models are methods used to quantify asymmetry using indexes and ratios. Symmetry index (SI), symmetry ratio (SR) and symmetry angle (SA) are the most commonly used models to quantify asymmetry.[7] In addition to the current models, recent literature has proposed a new model, 'modified symmetry index' (MSI).[7]

The mathematical models are given as follows:

$$\mathrm{SI}^{8}\ (\text{in }\%) = \frac{\mathrm{XR}-\mathrm{XL}}{0.5(\mathrm{XR}+\mathrm{XL})}\times 100, \tag{1}$$

$$\mathrm{SR}^{9}\ (\text{in ratio}) = \frac{\mathrm{XR}}{\mathrm{XL}}, \tag{2}$$

$$\mathrm{SA}^{10}\ (\text{in }\%) = \frac{45^{\circ}-\arctan(\mathrm{XL}/\mathrm{XR})}{90^{\circ}}\times 100, \tag{3}$$

$$\mathrm{MSI}^{7}\ (\text{in }\%) = \frac{\mathrm{XR}-\mathrm{XL}}{\text{Body weight}}\times 100, \tag{4}$$

where XR and XL represent WD (loading) on right and left sides respectively.

The SI is the widely used mathematical model, which quantifies WD in percentage of unit value such as kilograms or Newtons.[8] A value of SI = 0 indicates perfect symmetry in WD and any other values indicates asymmetrical WD on bilateral lower limbs.

The SR is the mathematical model, which compares the right limb loading values against the left limb. It gives the numerical relation of limb loading with respect to the right limb over the left. A value of SR = 1 designates symmetry and any other value indicates asymmetry.

The SA is a composite mathematical model, which uses trigonometry to quantify symmetry or asymmetry on bilateral lower limbs. A value of SA = 0 indicates symmetry and other values specify asymmetry.

The MSI model is adapted from the symmetry index. The output of the model is given in units of percentage. A score of MSI = 0 denotes symmetrical WD on lower extremities. The magnitude of asymmetry is interpreted from the value of the MSI score and the direction of asymmetry from its positive or negative sign value. A positive value indicates that the affected extremity is weight bearing more than the unaffected/healthy extremity, and the negative value implies *vice versa*. Testing the mathematical models using hypothetical data proved the MSI model as a notable model.[7] However, the competence and application of the MSI model in human data are not known. Additionally, no studies have compared the efficiency of these mathematical models in different populations reflecting varied magnitudes of limb load asymmetries.

2. Aim

The aim of this study is to investigate the efficacy of the mathematical model SI, MSI, SR and SA in healthy population and different clinical population (stroke and total knee replacement).

3. Material and methods

3.1. *Participants*

A total sample of 188 participants was recruited through convenience sampling for this study. The samples consist of 149 healthy participants, 27 participants with stroke and 12 participants with unilateral total knee replacement (TKR). This cross-sectional study was conducted at the musculoskeletal research laboratory in a public university teaching hospital. The inclusion criteria were set based on participants who could stand independently and could understand simple verbal comments. Healthy participants had no clinical signs and symptoms of orthopedic and neurological disease or disorder. Sample participants were excluded if they have any signs of cognitive, visual, or hearing impairment, inability to stand without walking aids and any other impairment, which prevents them from standing independently. The study protocol is approved by the public university research ethics committee. Informed consent was obtained from participants prior to their participation in this study.

3.2. *Procedure*

The limb loading data is measured from healthy population and clinical populations, in order to test data, which could comprise of small to large patterns of asymmetries. Secondly, testing on different clinical and non-clinical populations could reveal the strength and weakness of the model. The WD on lower limbs is quantified with two digital weighing scales (DWSs), A and B. Previous studies show the method of using two DWSs to measure WD on bilateral lower extremities as reliable (ICC 0.95–0.98).[11] The protocol for the measurement is adapted from Kumar et al.[11] The two DWSs of the same brand (BEU-GS27–007, Beurer, Germany) and specification are chosen. Prior to data collection, the two DWSs are tested with standard test loads to ensure no uncertainty between the scales. In addition, calibrations of the DWS are also done with each patient by ensuring zero in the display. Two DWSs are placed side to side with participant's shoulder width apart. Participants are asked to step on the DWS with each foot placed centrally over the equipment. Participants are encouraged to relax with arms at the sides, to capture their habitual standing posture. Followed by 10 s of standing, the limb loading measurement is recorded. Three trials were repeated and averaged for computation to reduce random error.

3.3. *Data analysis*

The raw data from limb loading measurement (in kg) obtained from bilateral lower limbs are further computed with mathematical models to evaluate the pattern of asymmetry (in percentage) in the limb load measurement. To compare the mathematical models, a standard reference value (RV) is calculated from the difference in the WD between right and left lower extremities as given below:

$$RV = XR - XL. \quad (5)$$

For the clinical population, the XR (loading on right) and XL (loading on left) can be substituted with X affected (affected limb) and X unaffected (unaffected limb), respectively for computation.

3.4. *Statistical analysis*

The data were analyzed using the statistical package for social sciences SPSS (IBM Inc., Chicago, Il) v. 20.00. Descriptive statistics such as mean, standard deviation, and range were calculated and compared. Individual analysis was carried out for healthy and each clinical condition to analyze the effectiveness of each model against the reference value. To test the measure of the strength, direction of association between the reference value and the mathematical model Pearson's correlation coefficient was employed. Statistical significance level is defined as $P < 0.05$ and the confidence level of 0.95. Further, scatter plots were constructed using Microsoft Excel v. 2010 visually to compare the pattern of the mathematical model against the reference value.

4. Results and discussion

In clinical practice, interpretation of pattern of symmetry/asymmetry in WD on bilateral lower extremity is essential in diagnosis of spine and lower extremity pathologies. Previous literature have tested and compared these mathematical models using simulated hypothetical data.[7] Hypothetical testing alone is not enough to confirm the competence of these models. The clinical usefulness of these models is established only by testing these models in different clinical population and healthy normative population.

The study findings on bilateral lower limb WD are discussed in line with the RV (Table 1). The RV reflects the absolute similarity or difference in WD on bilateral lower limbs. A value of zero in RV indicates symmetrical WD and values above or below reveals asymmetry. Hence, the value of the difference of the RV is directly proportional to the asymmetry. The descriptive statistics of SI show that the mean, SD and range values are higher when compared to other models. The maximum range of SI was revealed as a blown-up value of 197.20 in TKR, which is more than 100%. In contrast, the SR model shows a small mean, SD and range. The RV shows a wide variation in the SD and range in clinical and non-clinical data; however, it was not reflected in the SR model. The range was shown to be too narrow in SR model when compared to other models and RVs. Hence, SR is not reflecting the true magnitude of the WD asymmetry in the given population. Moreover, there is no positive or negative sign shown in any of the SR values, suggesting that the SR model is not able to give the direction or side of asymmetry.

Table 1 – Descriptive statistics.

	N	Mean ± SD	Minimum	Maximum
Healthy				
Reference	149	0.74 ± 3.47	−7.46	7.10
SI		2.35 ± 10.9	−28.47	29.45
MSI		1.17 ± 5.42	−14.34	14.75
SR		1.02 ± 0.11	0.75	1.35
SA		−0.74 ± 3.46	−9.31	9.00
Stroke				
Reference	27	1.38 ± 9.64	−11.98	11.00
SI		4.13 ± 28.48	−39.68	40.75
MSI		2.09 ± 14.26	−20.27	20.48
SR		1.08 ± 0.28	0.67	1.51
SA		−1.31 ± 8.99	−12.80	12.47
TKR				
Reference	12	11.99 ± 21.22	−14.08	70.50
SI		37.87 ± 61.48	−43.18	197.20
MSI		17.67 ± 27.78	−21.74	84.43
SR		12.19 ± 39.00	0.64	142.00
SA		−10.87 ± 16.74	−49.55	13.54

The SA model mean, SD and range are in proportion to the SI, MSI values and RV. However, the sign of the mean value is opposite to other models, and hence, the predicted direction of asymmetry is not reliable from this model. The MSI model demonstrates the mean, SD and range values to be consistent, which is corresponding with the RV, and it is almost half of the SI model. In addition, the MSI values are within 100% range, and hence easy to clinically interpret with a meaningful asymmetry pattern. Thus, MSI model is proved as a notable model as there is no inflation of values and manifest to be sensitive enough for high and low asymmetry values.

The results from the correlation analysis determine that the four models (SI, SR, SA, and MSI) are in significant relationship with the RVs (Table 2). The strength of the association is shown to be stronger as all the values of the correlation coefficients are close to ±1, except in SR model. SR model was having only a moderate association with the RV. This could be attributed to the low sensitivity, and the narrow minimum and maximum range value revealed by this model. Further, the SA model exhibits a negative correlation or an inverse relationship with the RV. The inverse relation point out that as the difference in WD between right and left lower limb (RV) increases, the WD asymmetry decreases (SA model).

Table 2 – Correlation of mathematical models against reference data.

Models	N	Pearson correlation (r)	Significance (2-tailed)
SI	188	0.98**	$P < 0.001$
MSI		0.97**	$P < 0.001$
SR		0.60**	$P < 0.001$
SA		−0.97**	$P < 0.001$

** Correlation is significant at 0.01 level (2-tailed).

This demonstrates that the SA model fails to predict a meaningful WD asymmetry value necessary for clinical interpretation. In consequence, SI and MSI exhibit to be a better model in accordance with the strong positive relationship demonstrated against the RV. However, in the descriptive analysis, SI shows inflated values.

The 2D line graph (Figs. 1–3) is discussed by comparing the four mathematical models against the reference line. The reference line is drawn from the RV, which is the difference in the WD on bilateral lower extremity. The SI and MSI graph trends are collateral with the reference line in all the sample populations. However, the SI graphs show there is a rise, reaching peak values in all sampling groups when compared to other models. Thus, it is evident from the graph trends that SI values are inflated, and shown to be bloated when compared against other models. The SR graph trend shows to be nearer to the x-axis zero line and not corresponding to the reference line pattern. The SR graph trend demonstrates a level off or even out pattern without any rise or fall in all the groups. Similarly, the SA line trends are not in analog with the trend of RV. In addition, the SA trend shows to be opposite to that of RV, MSI and SI line trends. Therefore, the graphical comparisons of the models conclude the MSI to be a noteworthy model.

In summary, the SI model demonstrates to have good sensitivity to sense differences in bilateral lower limb WD. However, the SI model has problems of inflation in higher asymmetry values. This is in support of our previous hypothetical testing of this model, in which the model output shows to be inflated up to 200%.[7] In another study, conducted

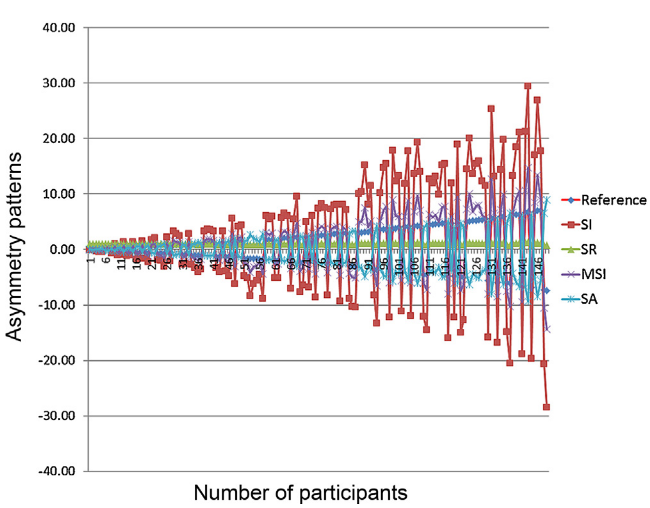

Fig. 1 – Mathematical models representing loading patterns in healthy participants.

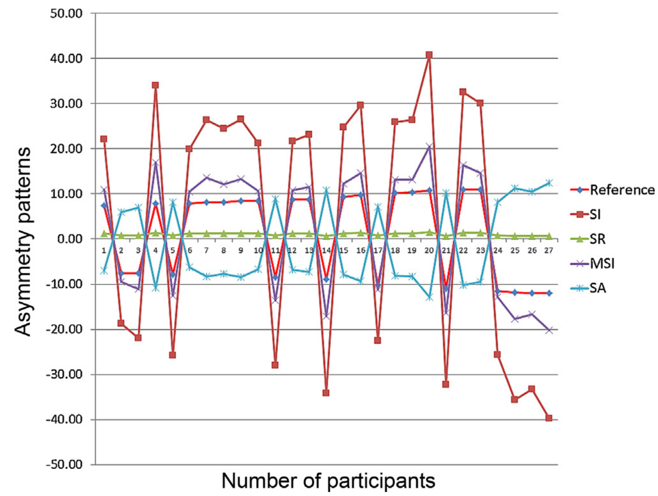

Fig. 2 – Mathematical models representing loading patterns in participants with stroke.

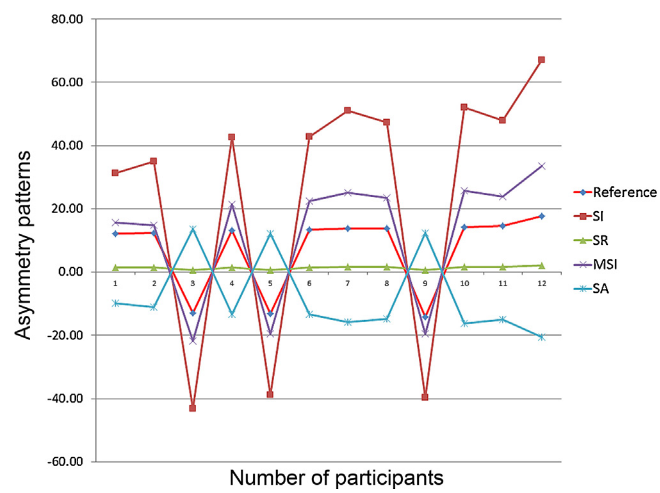

Fig. 3 – Mathematical models representing loading patterns in participants who had undergone TKR.

in normal human gait, it was proved that the SI model indicated an inflation value of 4% to 13 000% in ground reaction force variable.[12] The second model, SR, exhibits low sensitivity to differences in WD, and did not provide the magnitude and direction of absolute WD asymmetry. A study conducted in 25 hemiplegic participants on temporal gait asymmetries confirms that the SR model fails to detect the side and the degree of asymmetry.[13] Previous hypothetical testing of SR model also highlighted similar limitations.[7] The magnitude of asymmetry shown by the third model, SA, is close to RV when the difference in WD is minimal. The SA uses a complex mathematical formula, which is difficult to cognize by the clinicians. Previous hypothetical testing of SA model demonstrates that the values diverge between 50 and infinity (∞) and are not clinically meaningful.[7] The final model, MSI, is established to have better sensitivity to differences in WD and is able to quantify the side and extend of asymmetries in WD data as postulated by Kumar et al.[11]

The limitation of this study is that the sample size is not equally distributed between the clinical conditions and unilateral TKR population had a small sample size ($n = 12$). Nevertheless, this study did not compare between clinical conditions, and instead, the efficacy of mathematical model is compared individually to the clinical conditions. In addition, the mathematical models are compared in asymmetries and pertained to lower limb WD. However, the mathematical models are not tested in other asymmetries related to human movement patterns such as asymmetries in joint angle, acceleration, and gait parameters. Based on the results from clinical and non-clinical population, this study proposes the compliance of the mathematical model to quantify WD asymmetries on bilateral lower extremities in the hierarchical paradigm – MSI, SI, SA, and SR. The hierarchical paradigm could be generalizable in asymmetries related to lower limb WD.

5. Conclusions

The MSI is superior to other mathematical models. MSI provides magnitude and direction of WD asymmetry on bilateral lower limbs. MSI is simple to interpret, as the asymmetry output is in percentage value. MSI is shown to be stable, repulse to inflation and highly sensitive to quantify low and high WD asymmetries. Hence, MSI could be a notable model to quantify WD asymmetries in clinical and non-clinical populations.

Conflict of interest

None of the authors have a potential conflict of interest related to the manuscript or the work it describes.

Acknowledgements

We thank Dr. Leonard Henry Joseph for his guidance and assistance with study administration. Ministry of higher education fund supported this study – ERGS grant (ERGS/1/2013/SKK10/UKM/02/2). The grant funding had no role in the study design, data collection, analysis, or writing of this manuscript.

REFERENCES

1. Talis VL, Grishin AA, Solopova IA, Oskanyan TL, Belenky VE, Ivanenko YP. Asymmetric leg loading during sit-to-stand, walking and quiet standing in patients after unilateral total hip replacement surgery. *Clin Biomech*. 2008;23(4):424–433.
2. Cheng PT, Wu SH, Liaw MY, Wong AM, Tang FT. Symmetrical body-weight distribution training in stroke patients and its effect on fall prevention. *Arch Phys Med Rehabil*. 2001;82(12):1650–1654.
3. Harato K, Nagura T, Matsumoto H, Otani T, Toyama Y, Suda Y. Extension limitation in standing affects weight-bearing asymmetry after unilateral total knee arthroplasty. *J Arthroplasty*. 2010;25(2):225–229.
4. Schmid M, Beltrami G, Zambarbieri D, Verni G. Centre of pressure displacements in trans-femoral amputees during gait. *Gait Posture*. 2005;21(3):255–262.
5. Hurkmans HL, Bussmann JB, Benda E, Verhaar JA, Stam HJ. Techniques for measuring weight bearing during standing and walking. *Clin Biomech (Bristol Avon)*. 2003;18(7):576–589.
6. Kumar NS, Omar B, Joseph LH, et al. Accuracy of a digital weight scale relative to the Nintendo Wii in measuring limb load asymmetry. *J Phys Ther Sci*. 2014;26(8):1205.
7. Kumar SN, Omar B, Joseph LH. Evaluation of limb load asymmetry using two new mathematical models. *Glob J Health Sci*. 2014;7(2):1.
8. Robinson RO, Herzog W, Nigg BM. Use of force platform variables to quantify the effects of chiropractic manipulation on gait symmetry. *J Manipulative Physiol Ther*. 1987;10(4):172–176.
9. Pereira LC, Botelho AC, Martins EF. Relationships between body symmetry during weight-bearing and functional reach among chronic hemiparetic patients. *Braz J Phys Ther*. 2010;14(3):259–266.
10. Zifchock RA, Davis I, Higginson J, Royer T. The symmetry angle: a novel, robust method of quantifying asymmetry. *Gait Posture*. 2008;27(4):622–627.
11. Kumar SN, Omar B, Htwe O, et al. Reliability, agreement, and validity of digital weighing scale with MatScan in limb load measurement. *J Rehabil Res Dev*. 2014;51(4):591–598.
12. Herzog W, Nigg BM, Read LJ, Olsson E. Asymmetries in ground reaction force patterns in normal human gait. *Med Sci Sports Exerc*. 1989;21(1):110–114.
13. Wall JC, Turnbull GI. Gait asymmetries in residual hemiplegia. *Arch Phys Med Rehabil*. 1986;67(8):550–553.