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Gait variability and stability measures: Minimum number of strides and within-session reliability

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ABSTRACT

Background: Several methods are proposed in the literature for the quantification of gait variability/stability from trunk accelerations. Since outputs can be influenced by implementation differences, reliability assessment and standardization of implementation parameters are still an issue. The aim of this study is to assess the minimum number of required strides and the within-session reliability of 11 variability/stability measures.
Method: Ten healthy participants walked in a straight line at self-selected speed wearing two synchronized tri-axial Inertial Measurement Units. Five variability measures were calculated based on stride times namely Standard deviation, Coefficient of variation, Inconsistency of variance, Nonstationary index and Poincaré plot. Six stability measures were calculated based on trunk accelerations namely Maximum Floquet multipliers, Short term/long term Lyapunov exponents, Recurrence quantification analysis, Multiscale entropy, Harmonic ratio and Index of harmonicity. The required minimum number of strides and the within-session reliability for each measure were obtained based on the interquartile range/mean ratio. Measures were classified in five categories (namely excellent, good, average, poor, and very poor) based on their reliability.
Results: The number of strides required to obtain a reliable measure was generally larger than those conventionally used. Variability measures showed average to poor reliability, while stability measures ranged from excellent to very poor reliability.
Conclusion: Recurrence quantification analysis and multiscale entropy of trunk accelerations showed excellent reliability and a reasonable number of required strides. Based on these results, these measures should be taken into consideration in the assessment of fall risk.

1. Introduction

Ageing and pathology can worsen gait performance at multiple levels and in selective ways [1], and quantitative assessment of gait pattern has been proven to be useful in the early identification and prediction of pathology or cognitive decline [2–4]. In particular, trunk acceleration-based measures of gait variability and stability are proposed in the literature aiming at quantifying subject specific gait characteristics such as gait impairment, degree of neuro-motor control and balance disorders, in pathologic and healthy subjects, and are often related to fall at risk [5–9]. However, no standard implementation procedure for these measures is defined, potentially explaining the incoherent conclusions [10], as implementation differences can affect outputs. Thus, a standardization of the implementation parameters is necessary to perform a consistent evaluation. Moreover, these measures must reproduce the same results in the same experimental conditions.

Many strides can be required to obtain reliable measures, but treadmill walking differs significantly from over-ground walking [11]; hence, long walking trials have to be analyzed. The use of Inertial Measurement Units (IMU) allows to obtain both stride time variability and stability measures from trunk acceleration signals during long over-ground outdoor walking trials.

In order to further define implementation features for future effective exploitation of measures in research or clinical practice, an assessment of the repeatability of variability/stability measures is hence needed, together with an assessment of the number of necessary strides. The aim of the present study was to assess the minimum number of required strides and the within-session reliability of 11 temporal variability/stability measures proposed in the literature and applied to stride time and trunk accelerations during over-ground walking.

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2. Methods

Ten healthy participants [28 ± 3 years, 174 ± 11 cm, 67 ± 13 kg] walked in a straight line at self-selected natural speed on a 250 m long dead-end road (about 180 strides), wearing two synchronized tri-axial IMU (Opal, APDM, USA) located on the trunk (at the level of the fifth lumbar vertebra) and on the right shank. Sample size was chosen in agreement with previous literature [12]. Range of accelerometers was ± 6 G and sampling rate 128 Hz. Right heel strike instants were obtained from the angular velocity measured by the sensor on the shank with a wavelet-based method [13]. Gait initiation and termination phases were excluded. The average walking speed was 1.43 ± 0.15 m/s.

Since our aim was the characterization of variability/stability measures from a strictly methodological point of view, adequately segmented data coming from the same experimental trial (long overground walk) were analyzed. This approach was adopted in order to maintain the experimental conditions unvaried, being thus able to ascribe every variation found in the results to the intrinsic variability of each measure only rather than to actual differences in gait patterns depending on specific trial analyzed.

The following variability measures were applied to stride time:

i. Standard deviation (SD) [14];
ii. Coefficient of variation (CV) [14];
iii. Inconsistency of variance (IV) [15];
iv. Nonstationary index (NI) [15];
v. Poincaré plots (PSD1/PSD2) [16].

SD represents the standard deviation of stride time. CV is the variability of stride time normalized to the mean stride time value (CV = 100 × SD/mean) [14]. IV and NI quantify the temporal "structure" of the time series (independent of the overall variance); each time series was first normalized with respect to its mean and SD and then divided into blocks of five strides each. In each segment, the local average and the local SD were computed. NI is then defined as the SD of the local averages, while IV is defined as the SD of the local SDs [15]. Stride time data plots between successive gait cycles, known as Poincaré plots, show variability of stride time data. Statistically, the plots display the correlation between consecutive stride times data in a graphical manner. PSD1 and PSD2 represent, respectively, width and length of the long and short axis describing the elliptical nature of the plots, and hence the short-term and long-term variability of stride time [16].

The following stability measures were calculated on trunk accelerations in vertical (V), medio-lateral (ML) and anterior–posterior (AP) directions:

vi. Maximum Floquet multipliers (maxFM) [5,10];
vii. Short term/long term Lyapunov exponents (sLE/lLE) [5];
viii. Recurrence quantification analysis (RQA) [17];
ix. Multiscale entropy (MSE) [18];
x. Harmonic ratio (HR) [6];
xi. Index of harmonicity (IH) [19].

maxFM quantify orbital stability of a periodic or pseudo-periodic dynamic system, that is the tendency of the system state to return to the periodic limit cycle orbit after small perturbations [5,10]. On the other hand, sLE and lLE quantify local dynamic stability of a system and are used for systems that do not necessarily exhibit a discernable periodic structure [5]. RQA provides a characterization of a variety of features of a given time series, including a quantification of deterministic structure and non-stationarity [17], based on the construction of recurrence plots [20]. All of these measures imply the reconstruction of the state space of the system; in this study, four different state spaces were constructed: one 3-dimensional state space composed by acceleration signals in the V, ML and AP direction and three (one per direction) 5-dimensional state spaces composed by delay-embedding of each acceleration component (delay = 10 samples). Such parameters were chosen based on previous literature, stating that an embedding dimension of 5 and a 10 samples delay are appropriate for gait data [21–23], and on a false nearest neighbors analysis performed on our data.

Several measures were extracted from RQA, namely recurrence rate (rr), determinism (det), averaged diagonal line length (avg), maximum diagonal line length (max) and divergence (diverg). In the calculation of RQA measures, a radius of 40% was chosen to make sure that recurrence rate (rr) responded smoothly and was not too high, and that determinism (det) did not saturate at the floor of 0 or the ceiling of 100, as approaching these limits would tend to suppress variance in the measure [20]. Time series derived from complex systems, like biological systems, are likely to present structures on multiple spatio-temporal scales; MSE has been introduced to quantify the complexity or irregularity of a time series [18]. MSE has been obtained calculating sample entropy (consecutive data points $m=2$, distance $r=0.2$ [24]) on six consecutively more coarse-grained (scale factor $\tau=1, \ldots, 6$) time series. HR quantify the smoothness of acceleration patterns of the trunk based on amplitudes in the frequency spectra. It provides information on how smoothly subjects control their trunk during walking and it is directly related to whole body balance and coordination [6,25]. In this study, HR was not calculated stride by stride, but decomposing the whole signal into its harmonics [7]. Similarly to HR, IH assesses the contribution of the oscillating components to the observed coordination patterns by means of spectral analysis [19], quantifying the contribution of the stride frequency to the signal power relative to higher harmonics.

For the quantification of the **minimum number of strides**, measures were calculated on windows of decreasing length (from 150 to 10 strides, 1 stride resolution). Interquartile range and median value of measures were calculated for all the windows. Percent interquartile range/median ratio (*imr*) was then calculated, starting from the 150 strides window (which gave the lowest ratio) and proceeding backwards.

Adding an increasing number of strides to the calculation would cause the measure to reach a steady outcome, which represents a compromise between reliability of the measure and experimental limitations. Percent *imr* is then an indication of the variations of the measures around the median value. A low *imr* indicates small variations of the measure around its median value with the increase of the number of strides; this means that the measure reached a steady value, and it is not likely to change with the inclusion of further strides. On the contrary, a high *imr* indicates that the measure undergoes significant variation with the increase of the number of strides, and hence is still not fully reliable.

Thresholds for the *imr* were fixed at 10%, 20%, 30%, 40% and 50%. The required number of strides was defined as the smallest one at which the ratio remained below the lowest possible threshold. The minimum number of strides was calculated per index and per subject at first, and then the largest number of strides over subjects was selected for each index.

The assessment of **within-session reliability** was performed calculating variability/stability measures on a window sliding along the trial with 1 stride steps. The sliding window size was set to 85 strides, since most measures (51 out of 57) required less than 85 strides. lLE (tot, V, ML, AP) and RQA V (max, diverg) did not satisfy this criterion. Interquartile range and median values of the measures over the windows, together with the percent *imr* for each measure, were calculated. Measures were grouped in five reliability categories, ranging from very poor ($imr > 40\%$) to excellent ($imr < 10\%$), based on the maximum inter-subject *imr*.

Interquartile range/median ratio was chosen as a reliability measure since large magnitude variations around the median value (particularly among windows sharing a lot of data) can be potentially disruptive, and are to be considered as a sign of low repeatability and high intrinsic variability of the measure.

In addition, intra-class correlation (ICC 2,1) was calculated between two 85 strides non-overlapping windows extracted for each subject from the same walking trial (SPSS Statistics 20.0, IBM, Armonk, NY, USA).

3. Results

Measures reached steady values for different numbers of strides, depending on the threshold. For MSE V (τ=1, …, 4) and RQA (AP rr, det, avg, ML rr and V rr, det, avg), 10 strides were sufficient to reach a 10% threshold. MSE (AP, ML, V τ=5,6), RQA (ML det, avg) and sLE V reached a 20% threshold within 10 strides. Other measures showed lower stride number requirement with the increasing of the threshold. lLE required a high number of strides ($>$110) even for the 50% threshold. RQA (V max, diverg) never reached steady values in the analyzed range (Table 1).

MSE and RQA (rr, det, avg) showed excellent reliability. HR and sLE demonstrated average to good reliability, with the exception of sLE (tot) that performed poorly. Temporal variability measures (SD, CV, IV, NI and PSD) showed from poor to good reliability. IH showed poor reliability, particularly in AP and V directions. lLE, maxFM and RQA (max, diverg) showed very poor reliability. Reliability results are shown in Table 2. The median values of inter-subjects medians and inter-quartiles for variability/stability measures, together with maximum *imr* values, are also shown. These values are meant as reference for the analyzed measures in healthy subjects.

ICC results showed overall coherence with *imr* values, highlighting similar correlation patterns, with the main exception of IH (AP, V) results (Table 3).

Table 1
Number of required strides for each measure at each threshold.

Variability/stability measures	Thresholds				
	10%	20%	30%	40%	50%
SD	125	59	20	15	10
CV	127	59	49	15	10
NI	143	97	89	78	70
IV	143	91	44	35	29
PSD1	127	52	16	15	10
PSD2	120	106	74	25	19
MSE AP τ=1	19	10	10	10	10
MSE AP τ=2	19	10	10	10	10
MSE AP τ=3	18	10	10	10	10
MSE AP τ=4	15	10	10	10	10
MSE AP τ=5	35	10	10	10	10
MSE AP τ=6	17	10	10	10	10
MSE ML τ=1	10	10	10	10	10
MSE ML τ=2	30	10	10	10	10
MSE ML τ=3	63	10	10	10	10
MSE ML τ=4	31	10	10	10	10
MSE ML τ=5	10	10	10	10	10
MSE ML τ=6	32	10	10	10	10
MSE V τ=1	10	10	10	10	10
MSE V τ=2	10	10	10	10	10
MSE V τ=3	10	10	10	10	10
MSE V τ=4	10	10	10	10	10
MSE V τ=5	12	10	10	10	10
MSE V τ=6	15	10	10	10	10
RQA AP (rr)	10	10	10	10	10
RQA AP (det)	10	10	10	10	10
RQA AP (avg)	10	10	10	10	10
RQA AP (max)	121	75	74	37	36
RQA AP (diverg)	107	95	74	74	74
RQA ML (rr)	10	10	10	10	10
RQA ML (det)	78	10	10	10	10
RQA ML (avg)	55	10	10	10	10
RQA ML (max)	136	129	73	29	29
RQA ML (diverg)	136	135	79	29	29
RQA V (rr)	10	10	10	10	10
RQA V (det)	10	10	10	10	10
RQA V (avg)	10	10	10	10	10
RQA V (max)	150	150	150	150	150
RQA V (diverg)	150	150	150	150	150
HR AP	141	26	15	10	10
HR ML	137	30	10	10	10
HR V	66	29	10	10	10
IH AP	143	141	137	75	10
IH ML	145	141	49	10	10
IH V	140	127	120	18	11
maxFM tot	137	135	23	10	10
maxFM AP	138	137	132	10	10
maxFM ML	137	131	14	10	10
maxFM V	137	51	20	10	10
sLE tot	105	70	10	10	10
sLE AP	90	17	10	10	10
sLE ML	72	10	10	10	10
sLE V	63	10	10	10	10
lLE tot	139	132	130	128	124
lLE AP	141	135	132	131	129
lLE ML	146	125	119	114	110
lLE V	138	123	121	116	113

4. Discussion

While variability measures aim at quantifying the degree of variability in the stride time, stability measures directly quantify stability (maxFM, sLE, lLE) or stability-related properties of gait time-series, such as recurrence (RQA), complexity at different scales (MSE), smoothness (HR) or harmonicity (IH). Since no standard implementation procedure is defined for these measures, the aim of this study was to investigate the required minimum number of strides and the within-session reliability of a number of gait variability/stability measures.

Prior research explored similar questions [26,27], but based solely on treadmill walking. Other studies recently focused on the assessment of reliability of gait stability and variability measures [28,29], confirming that the reliability of variability parameters improves with the increase in the number of analyzed cycles.

Since data extracted from the same overground long walk were analyzed, experimental conditions were guaranteed to be the same allowing to ascribe the differences found in the results to intrinsic features of the measures only, rather than to actual differences in the gait pattern adopted by the participants.

In general, measures showed comparable performances between the reliability indication and the threshold reached for a corresponding number of strides (85). MSE (ML τ=1, 5 and V τ=1, …, 4) and RQA (AP rr, det, avg, ML rr and V rr, det, avg) reached a steady value for a 10% threshold within 10 strides. MSE and RQA (rr, det, avg) also showed excellent reliability. sLE (ML, V) showed that the 10% threshold could be reached for 85 strides, but inter-subject *imr* was slightly higher (0.20 and 0.28 respectively); this is likely due to the influence of the inherent variability of the trial.

SD and CV showed average reliability and quite a high number of strides (125 and 127, respectively) to undergo the 10% threshold. This confirms findings from other studies stating that a few number of strides may not be sufficient to obtain reliable measures for both young subjects and old adults [30,31].

A large number of required strides was found for lLE and RQA (V max, diverg). lLE measure required at least 110 strides to reach

Table 2
Reliability grouping of variability and stability measures. Measures have been grouped based on the maximum inter-subject *imr*. Reliabilities have been labeled as very poor (*imr* > 40%), poor (*imr* = 30–40%), average (*imr* = 20–30%), good (*imr* = 10–20%), excellent (*imr* < 10%). As an indication of reference values for the measures, median values of inter-subjects' medians and interquartiles for variability/stability measures are also shown. Units of measurement legend: MSE – unitless, RQA (rr, det) – % of points on the recurrence plot, RQA (avg, max, diverg) – number of points on the recurrence plot, HR – unitless, IH – unitless, sLE – 1/stride, lLE – 1/stride, maxFM – unitless, SD – seconds, CV – unitless, NI – unitless, IV – unitless, and PSD1/PSD2 – seconds.

	Variability/stability measures	Maximum inter-subject *imr* (%)	Median inter-subject value of the medians	Median inter-subject interquartile value
Excellent	MSE AP $\tau=1$	7	0.38	0.01
	MSE AP $\tau=2$	7	0.56	0.02
	MSE AP $\tau=3$	6	0.65	0.02
	MSE AP $\tau=4$	7	0.76	0.02
	MSE AP $\tau=5$	8	0.81	0.02
	MSE AP $\tau=6$	7	0.85	0.02
	MSE ML $\tau=1$	8	0.59	0.01
	MSE ML $\tau=2$	8	0.86	0.02
	MSE ML $\tau=3$	7	1.09	0.03
	MSE ML $\tau=4$	6	1.31	0.03
	MSE ML $\tau=5$	6	1.46	0.04
	MSE ML $\tau=6$	6	1.55	0.04
	MSE V $\tau=1$	5	0.46	0.01
	MSE V $\tau=2$	5	0.63	0.02
	MSE V $\tau=3$	7	0.74	0.02
	MSE V $\tau=4$	9	0.84	0.03
	MSE V $\tau=5$	7	0.92	0.03
	MSE V $\tau=6$	9	1.00	0.03
	RQA AP (rr)	7	15.65	0.06
	RQA AP (det)	5	69.3	1.1
	RQA AP (avg)	7	8.94	0.12
	RQA ML (rr)	3	8.50	0.12
	RQA ML (det)	9	49.7	0.8
	RQA ML (avg)	7	6.67	0.12
	RQA V (rr)	6	13.76	0.22
	RQA V (det)	3	81.9	0.5
	RQA V (avg)	8	13.58	0.28
Good	HR AP	15	3.70	0.14
	HR ML	13	2.21	0.11
	HR V	16	4.68	0.24
	PSD1	14	0.021	0.001
Average	sLE AP	26	0.67	0.14
	sLE ML	20	0.81	0.14
	sLE V	28	0.89	0.19
	SD	23	0.02	0.002
	CV	23	1.94	0.14
Poor	IH ML	37	0.15	0.02
	PSD2	34	0.021	0.002
	sLE tot	39	0.44	0.10
	NI	30	0.52	0.10
	IV	37	0.32	0.06
Very poor	maxFM tot	57	0.36	0.09
	maxFM AP	45	0.43	0.08
	maxFM ML	44	0.39	0.06
	maxFM V	44	0.48	0.08
	IH AP	50	0.04	0.01
	IH V	55	0.022	0.003
	RQA AP (max)	66	399	51
	RQA AP (diverg)	164	0.0025	0.0003
	RQA ML (max)	88	281	39
	RQA ML (diverg)	69	0.0036	0.0004
	RQA V (max)	96	1986	481
	RQA V (diverg)	176	0.0005	0.0002
	lLE tot	89	0.035	0.007
	lLE AP	112	0.035	0.008
	lLE ML	52	0.014	0.004
	lLE V	57	0.041	0.007

the 50% threshold, while RQA (V max, diverg) never reached steady values in the analyzed range. IH, maxFM, sLE and RQA (max, diverg) showed poor or very poor reliability.

ICC results showed overall coherence with *imr* values. The main exception is represented by IH (AP, V). ICC of IH (AP, V) highlighted high correlation between the two analyzed windows, whereas the analysis of *imr* showed very poor correlation. This could be partially explained by the very small values reached by IH in AP and V directions (0.022–0.04), which could make *imr* calculation more prone to small instrumentation or numerical errors. ICC of RQA (max, diverg) was not as good as other RQA measures (rr, det, avg), but resulted slightly larger than what was obtained with *imr* observation. Coherently with the *imr* observation, ICC for some measures (maxFM, sLE tot, NI, lLE AP, ML) was very small or not significant.

Table 3
Intra-class correlation (ICC) of variability/stability measures calculated between two non-overlapping windows of 85 strides extrapolated from each experimental trial.

Measure	ICC	*p*-Value	Measure	ICC	*p*-Value
maxFM tot	−0.57	0.94	MSE V $\tau=1$	0.85	<0.05
maxFM AP	−0.23	0.74	MSE V $\tau=2$	0.87	<0.05
maxFM ML	−0.44	0.88	MSE V $\tau=3$	0.84	<0.05
maxFM V	−0.47	0.89	MSE V $\tau=4$	0.85	<0.05
HR AP	0.76	<0.05	MSE V $\tau=5$	0.86	<0.05
HR ML	0.90	<0.05	MSE V $\tau=6$	0.81	<0.05
HR V	0.95	<0.05	RQA AP (rr)	0.91	<0.05
IH AP	0.96	<0.05	RQA AP (det)	0.93	<0.05
IH ML	0.98	<0.05	RQA AP (avg)	0.94	<0.05
IH V	0.93	<0.05	RQA AP (max)	0.79	<0.05
PSD1	0.96	<0.05	RQA AP (diverg)	0.73	<0.05
PSD2	0.55	<0.05	RQA ML (rr)	0.99	<0.05
sLE tot	0.12	0.37	RQA ML (det)	0.98	<0.05
sLE AP	0.69	<0.05	RQA ML (avg)	0.93	<0.05
sLE ML	0.04	0.45	RQA ML (max)	0.68	<0.05
sLE V	0.68	<0.05	RQA ML (diverg)	0.79	<0.05
MSE AP $\tau=1$	0.96	<0.05	RQA V (rr)	0.96	<0.05
MSE AP $\tau=2$	0.97	<0.05	RQA V (det)	0.99	<0.05
MSE AP $\tau=3$	0.97	<0.05	RQA V (avg)	0.97	<0.05
MSE AP $\tau=4$	0.94	<0.05	RQA V (max)	0.68	<0.05
MSE AP $\tau=5$	0.94	<0.05	RQA V (diverg)	0.51	<0.05
MSE AP $\tau=6$	0.89	<0.05	NI	0.35	0.15
MSE ML $\tau=1$	0.92	<0.05	IV	0.49	<0.05
MSE ML $\tau=2$	0.89	<0.05	SD	0.85	<0.05
MSE ML $\tau=3$	0.91	<0.05	CV	0.82	<0.05
MSE ML $\tau=4$	0.90	<0.05	lLE tot	0.48	<0.05
MSE ML $\tau=5$	0.89	<0.05	lLE AP	0.42	0.08
MSE ML $\tau=6$	0.82	<0.05	lLE ML	0.41	0.08
			lLE V	0.53	<0.05

In conclusion, only MSE and RQA (rr, det, avg) showed excellent reliability. In a previous work [7] it was found that MSE and RQA calculated during treadmill walking correlated with fall history; these findings suggest a possible future clinical application in the definition of a more valid and robust fall risk index. Further research on the relationship of such measures with overground gait stability in old adults and pathologic subjects is highly encouraged.

In general, the number of strides necessary to obtain a reliable measure was larger than those conventionally used in the analysis of over-ground walking. Our results suggest carefulness when drawing conclusions about gait variability and stability obtained from short walking trials. A number of strides coherent with the indications illustrated in Table 1 should always be considered.

Conflict of interest statement

None declared.

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References

[1] S. Lord, B. Galna, L. Rochester, Moving forward on gait measurement: toward a more refined approach, Mov. Disord. 28 (2013) 1534–1543.
[2] A. Mirelman, T. Gurevich, N. Giladi, A. Bar-Shira, A. Orr-Urtreger, J.M. Hausdorff, Gait alterations in healthy carriers of the LRRK2 G2019S mutation, Ann. Neurol. 69 (2011) 193–197.
[3] J. Verghese, C. Wang, R.B. Lipton, R. Holtzer, X. Xue, Quantitative gait dysfunction and risk of cognitive decline and dementia, J. Neurol. Neurosurg. Psychiatry 78 (2007) 929–935.
[4] G. Abellan van Kan, Y. Rolland, S. Andrieu, J. Bauer, O. Beauchet, M. Bonnefoy, et al., Gait speed at usual pace as a predictor of adverse outcomes in community-dwelling older people an International Academy on Nutrition and Aging (IANA) Task Force, J. Nutr. Health Aging 13 (2009) 881–889.
[5] J.B. Dingwell, H.G. Kang, Differences between local and orbital dynamic stability during human walking, J. Biomech. Eng. 129 (2007) 586–593.
[6] H.B. Menz, S.R. Lord, R.C. Fitzpatrick, Acceleration patterns of the head and pelvis when walking on level and irregular surfaces, Gait Posture 18 (2003) 35–46.
[7] F. Riva, M.J.P. Toebes, M. Pijnappels, R. Stagni, J.H. van Dieën, Estimating fall risk with inertial sensors using gait stability measures that do not require step detection, Gait Posture 38 (2013) 170–174.
[8] D. Hamacher, N.B. Singh, J.H. Van Dieën, M.O. Heller, W.R. Taylor, Kinematic measures for assessing gait stability in elderly individuals: a systematic review, J. R. Soc. Interface 8 (2011) 1682–1698.
[9] J.M. Hausdorff, D.A. Rios, H.K. Edelberg, Gait variability and fall risk in community-living older adults: a 1-year prospective study, Arch. Phys. Med. Rehabil. 82 (2001) 1050–1056.
[10] F. Riva, M.C. Bisi, R. Stagni, Orbital stability analysis in biomechanics: a systematic review of a nonlinear technique to detect instability of motor tasks, Gait Posture 37 (2013) 1–11.
[11] F. Alton, L. Baldey, S. Caplan, M.C. Morrissey, A kinematic comparison of overground and treadmill walking, Clin. Biomech. 13 (1998) 434–440.
[12] S.D. Walter, M. Eliasziw, A. Donner, Sample size and optimal designs for reliability studies, Stat. Med. 17 (1998) 101–110.
[13] K. Aminian, B. Najafi, C. Büla, P.-F. Leyvraz, P. Robert, Spatio-temporal parameters of gait measured by an ambulatory system using miniature gyroscopes, J. Biomech. 35 (2002) 689–699.
[14] J.M. Hausdorff, A. Lertratanakul, M.E. Cudkowicz, A.L. Peterson, D. Kaliton, A.L. Goldberger, Dynamic markers of altered gait rhythm in amyotrophic lateral sclerosis, J. Appl. Physiol. 88 (2000) 2045–2053.
[15] J.M. Hausdorff, M.E. Nelson, D. Kaliton, J.E. Layne, M.J. Bernstein, A. Nuernberger, et al., Etiology and modification of gait instability in older adults: a randomized controlled trial of exercise, J. Appl. Physiol. 90 (2001) 2117–2129.
[16] A.H. Khandoker, S.B. Taylor, C.K. Karmakar, R.K. Begg, M. Palaniswami, Investigating scale invariant dynamics in minimum toe clearance variability of the young and elderly during treadmill walking, IEEE Trans. Neural Syst. Rehabil. 16 (2008) 380–389.
[17] F. Sylos Labini, A. Meli, Y.P. Ivanenko, D. Tufarelli, Recurrence quantification analysis of gait in normal and hypovestibular subjects, Gait Posture 35 (2012) 48–55.
[18] M. Costa, C.-K. Peng, A.L. Goldberger, J.M. Hausdorff, Multiscale entropy analysis of human gait dynamics, Phys. A: Stat. Mech. Appl. 330 (2003) 53–60.
[19] C.J.C. Lamoth, P.J. Beek, O.G. Meijer, Pelvis–thorax coordination in the transverse plane during gait, Gait Posture 16 (2002) 101–114.
[20] M. Riley, R. Balasubramaniam, M. Turvey, Recurrence quantification analysis of postural fluctuations, Gait Posture 9 (1999) 65–78.
[21] J.B. Dingwell, J.P. Cusumano, Nonlinear Time Series Analysis of Normal and Pathological Human Walking, 10, Chaos, Woodbury, N.Y. (2000) 848–863.
[22] S.A. England, K.P. Granata, The influence of gait speed on local dynamic stability of walking, Gait Posture 25 (2007) 172–178.
[23] S.M. Bruijn, J.H. van Dieën, O.G. Meijer, P.J. Beek, Statistical precision and sensitivity of measures of dynamic gait stability, J. Neurosci. Methods 178 (2009) 327–333.
[24] J.S. Richman, J.R. Moorman, Physiological time-series analysis using approximate entropy and sample entropy, Am. J. Physiol.Heart Circ. 278 (2000) H2039–H2049.
[25] K.A. Lowry, A.L. Smiley-Oyen, A.J. Carrel, J.P. Kerr, Walking stability using harmonic ratios in Parkinson's disease, Mov. Disord. 24 (2009) 261–267.
[26] H.G. Kang, J.B. Dingwell, Intra-session reliability of local dynamic stability of walking, Gait Posture 24 (2006) 386–390.
[27] T.M. Owings, M.D. Grabiner, Measuring step kinematic variability on an instrumented treadmill: how many steps are enough? J. Biomech. 36 (2003) 1215–1218.
[28] K.S. van Schooten, S.M. Rispens, M. Pijnappels, A. Daffertshofer, J.H. van Dieen, Assessing gait stability: the influence of state space reconstruction on inter- and intra-day reliability of local dynamic stability during over-ground walking, J. Biomech. 46 (2013) 137–141.
[29] N. Konig, N.B. Singh, J. von Beckerath, L. Janke, W.R. Taylor, Is gait variability reliable? An assessment of spatio-temporal parameters of gait variability during continuous overground walking, Gait Posture 39 (2014) 615–617.
[30] T.M. Owings, M.D. Grabiner, Variability of step kinematics in young and older adults, Gait Posture 20 (2004) 26–29.
[31] J.H. Hollman, K.B. Childs, M.L. McNeil, A.C. Mueller, C.M. Quilter, J.W. Youdas, Number of strides required for reliable measurements of pace, rhythm and variability parameters of gait during normal and dual task walking in older individuals, Gait Posture 32 (2010) 23–28.