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Movement variability emerges in gait as adaptation to task constraints in dynamic environments

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ABSTRACT

Background: Motor variability has been related to motor control playing a functional role in human adaptive behaviours. However, the direction of the relationship between variability and motor control can be unclear. The specific relations that exist between task constraints and movement (re)organization could explain some of this controversy.

Research question: This study sought to understand whether manipulation of task constraints result in changes in the magnitude or structure of motor system variability observed in a basic walking task. We also investigated the relationship between performance in achieving task goals and the structure of motor variability.

Methods: Twenty volunteers walked around a circular track with binary combinations of 3 task constraints, providing 8 conditions. The manipulated task constraints were: 1) track width; 2) surface stiffness; and 3), walking direction. Performance was analysed using standard deviation (SD) of sacral displacement and its mean velocity (MV). Fuzzy Entropy (FE) and Detrended Fluctuation Analysis (DFA) were used to assess the kinematic variability structure.

Results: Individuals showed lower SD and MV walking on the narrower track. These changes were also followed by higher DFA values, indicating a more auto-correlated structure of variability. The foam surface was also associated with an increase in amplitude, velocity and irregularity (FE) of movement.

Significance: Results of this study describe how specific task constraints, such as the width of the walking track and the surface stiffness, shape emergent movement coordination patterns as participants search for functional information from the environment to regulate performance behaviors. Changes in variability structure could reveal the search for adaptive strategies during walking. Smaller movement fluctuations and higher velocity in gait patterns are related to greater irregularity and lower autocorrelation in the kinematic variability structure, demonstrating that a specific relationship emerges between system variability and movement performance, which is driven by task constraints.

1. Introduction

Motor variability is inherent within neurobiological systems, playing a functional role in adaptive behaviours of humans [1,2], characterized by refinements in movement performance during interactions with environmental contexts [3]. Humans need to use motor variability to drive adaptive behaviours in changing environments [1]. This process can be observed during performance of numerous everyday motor tasks, such as locomotion, in which one constantly needs to adapt each step to a preceding one and every step is different.

For this reason, motor variability has been studied in different performance contexts to establish the movement (re)organization being used to achieve task goals [4,5] or to adapt to the effects of sensorimotor impairments [6,7]. However, the direction of the relationship between motor variability and motor control can be unclear. Some research on variability has associated it with performance impairment, such as when gait variability is related to balance deficits during walking (e.g [8,9].). However, other studies have proposed alternative explanations for such observations. For instance, Rosenblatt, Hurt [10] studied the relationship between variability of foot placement and stability of gait patterns. Using uncontrolled manifold analysis of the joint configuration variance, they distinguished two types of variability,

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defined as "good" (which did not affect the mediolateral trajectory of the foot in the frontal plane) and "bad" (which affected this trajectory). Their results suggested that larger amounts of good variability could improve stability. It suggests that motor variability could offer a window into the control structures that underlie behaviour regulation [11]. Humans appear to use different regulatory strategies to compensate for inherent motor limitations by exploiting motor system variability for successful task performance [12]. In other words, motor variability has a functional role to drive adaptive behaviours in movement systems, allowing the central nervous system to exploit the high dimensionality offered by the abundance of motor system degrees of freedom (DoF) [1].

During movement regulation, the role of perception and action is to support the (re)organization of intentional behaviours during interactions with environmental and task constraints [13]. Such constraints may shape adaptations to the (re)organization of motor system DoFs by structuring the state space of possible system configurations available. Some investigators have suggested that these continuous adaptations are reflected in the structure of motor variability [14], with the relationship between variability and motor control being influenced by task constraints. This hypothesis has been tested during performance in manual force control tasks [14] or standing balance tasks [2]. Evidence implies that specificity of task constraints may shape emergent motor system behaviours. Indeed, the specific relations that exist between task constraints and movement (re)organization could explain some of the controversy explained above regarding the relationship between variability and motor control [2].

To examine this issue, we sought to understand whether manipulation of task constraints would result in changes in the magnitude or structure of motor system variability observed in a walking task. We also investigated the relationship between performance in achieving task goals and the structure of motor variability. Gait variability provides insights on neuromotor performance regulation [6], and has been studied to assess effects of aging [8,15] and different disabilities [6,9]. Here, we analysed emergent movement adaptations under varying task constraints. Our prediction was that the structure of motor variability would depend on the specific task constraints to be satisfied. Specifically, we expected that changes in properties of a locomotion task would lead to a reduction in the number of available configurations in participant motor systems. These changes were expected to result in greater regularity in gait, and increased auto-correlations within the structure of movement variability.

2. Methods

2.1. Participants

Twenty healthy volunteers (8 females, 12 males) participated in this study (age = 26.6 ± 5.5 years; stature = 1.7 ± 0.1 m; mass = 69.4 ± 13.9 Kg). Exclusion criteria included current musculoskeletal injuries or balance deficits that impaired participants from walking safely along a track designed in a laboratory.

Written informed consent was obtained from participants prior to testing. The experimental procedures used were in accordance with the Declaration of Helsinki and were approved by Sheffield Hallam University Research Ethics Committee.

2.2. Experimental procedure and data collection

To assess postural dynamic balance, kinematic data from the pelvis were recorded at 120 Hz using an electromagnetic tracking system (Polhemus G4, Polhemus, USA). Pelvis displacement, in three axes (antero-posterior (AP), medio-lateral (ML) and vertical (V)), was recorded through an electromagnetic sensor firmly taped to the sacrum of each participant.

Participants walked around a circular track on the floor (Fig. 1) with binary combinations of 3 different task constraints, providing a total of 8 different conditions (Table 1). They walked barefoot to avoid any possible differences related to footwear. Manipulated task constraints were: 1) width of the walking track (0.15 or 0.30 m); 2) surface stiffness (foam or vinyl); and 3), walking direction (clockwise or anticlockwise). These task constraints were manipulated because they significantly impact on gait regulation in different ways: 1) the width of the walking track can constrain participant behaviour by modifying the need for precision of foot placement. For example, Young and Dingwell [16] showed how stability increased when participants had to walk with wider steps. In this study, we manipulated the width of the track to assess how the width of the steps, limited by space available, affects the involvement of motor system DoFs; 2) surface stiffness can play a role regulating the perception of sensorimotor information from the soles of the feet when walking [17]. The thickness of the foam used in this study was 5 cm; and 3), direction of walking could be related to the intrinsic dynamics (movement organisation tendencies) of each individual in adapting gait regulation to clockwise and anti-clockwise directions, for example. Some studies have shown that people tend to show a turning preference during locomotion [18,19]. We expected to find different strategies according to walking direction, since one is likely to be more stable than the other. Participants were instructed to walk in their typical way on the path and adjust their steps to a metronomic rhythm of 130 bpm, provided acoustically, in order to standardise step velocity. The duration of each test trial was 70 s and the rest period between trials was 1 min. Every condition was experienced twice by participants in a randomized order.

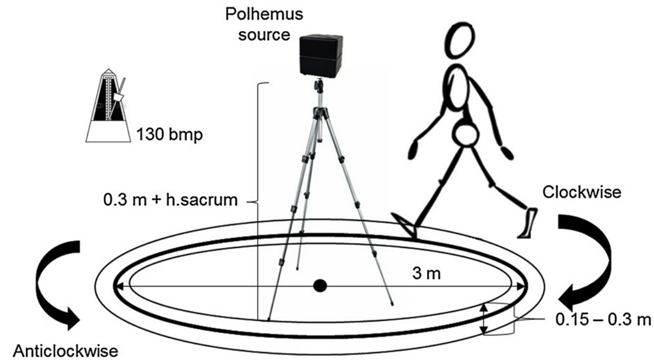

Fig. 1. Diagram of the experimental protocol.

Table 1
Constrains manipulated and conditions of each constraint.

CONSTRAINTS	CONDITIONS	
The width of a walking track	0.15 m (T)	0.3 m (W)
The surface stiffness	Foam (F)	Solid (S)
The direction of walking	Clockwise (C)	Anti-clockwise (AC)

2.3. Data analysis and reduction

An application written in Labview 2009 (National Instruments, Texas), developed in our laboratory, was used for data analysis. Data were already filtered by the G4 Polhemus tracking system with a single-pole, low-pass filter with an adaptive pole location. The pre-set filtering parameters were: sensitivity = 0.02; boundary (FLow) = 0.02: boundary (FHigh) = 0.8; Max transition rate = 0.95. Kinematic time series data were then down-sampled, by interpolation, from 120 Hz to 20 Hz. The first and last 5 s of each trial were discarded to avoid non-stationarity related to trial initiation and termination [20]. Time series length was 1200 data points.

Postural sway, used to assess task performance, was determined using standard deviation (SD) values of sacral displacement and its mean velocity (MV). Functional performance behaviour was defined in this study by lower dispersion and velocity of each participant's displacement trajectory. According to this definition, the best trial performed in each condition was selected for statistical analysis.

Variables used to assess the variability structure in kinematic data were Fuzzy Entropy (FE) and Detrended Fluctuation Analysis (DFA). Fuzzy Entropy values indicate the degree of irregularity in a signal: higher FE values indicate greater irregularity in the signal time domain, whereas lower FE values indicate greater regularity. To calculate this measure, the following parameter values were used: vector length, m = 2; tolerance window, r = 0.2*SD; and gradient, n = 2. These parameter values have been shown to have high consistency, which underlie their frequent use [21,22]. Detrended Fluctuation Analysis evaluates the presence of long-term correlations within a time series using a parameter known as the scaling index, α [23]. The α value identifies the extent to which proceeding data are dependent on previous outcomes [24]. Different values of α indicate the following: $\alpha > 0.5$ implies persistence; $\alpha < 0.5$ implies anti-persistence; and $\alpha = 0.5$ implies an uncorrelated signal [25]. In the current study, this measure was computed according to procedures recommended by Peng, Havlin [23]. The slope α was obtained from the window range $4 \le n \le N/10$ to maximize the long-range correlations and reduce errors incurred by estimating α [26].

Dependent variables were calculated over the resultant distance (RD) kinematic time series, instead of the AP, ML and V axes, in order to obtain a global variable. RD is the vector distance from the centre of the circular track negotiated by participants (where the Polhemus G4 source was placed) to the sensor placed on the sacrum.

$$RD\ time\ series = \sqrt{(X[n] - \bar{X})^2 + (Y[n] - \bar{Y})^2 + (Z[n] - \bar{Z})^2}\ n = 1,2,\ \dots,\ N.$$

where n is the number of data points in the kinematic time series. X, Y and Z correspond to values of the kinematic time series for AP, ML and V axes, successively and, $\bar{X}$, $\bar{Y}$ and $\bar{Z}$ correspond to the means of the kinematic time series for the AP, ML and V axes, respectively.

2.4. Statistical analysis

Normality of variable distribution was evaluated using the Kolmogorov-Smirnov test with the Lilliefors correction. A repeated measures ANOVA with three intra-individual variables, width of a walking track, surface path and walking direction, was used to assess effects of constraints manipulations on performance outcome measures and nonlinear variables. Alpha levels were set at $p < 0.05$. Partial eta squared (η_p^2) was calculated as a measure of effect size and to record the proportion of the overall variance attributable to each factor. Values of effect size above 0.64 were considered strong, between 0.25 and 0.64 for moderate and bellow 0.25 small [27]. Finally, Pearson Product Moment Correlation coefficients were calculated to assess relationships between performance variables (Displacement SD and MV) and nonlinear measures of variability (FE and DFA).

3. Results

Average values obtained in every walking condition are displayed in Table 2.

None of the dependent variables showed significant differences between clock and anti-clockwise walking directions (Table 3). The most sensitive variables to this constraint were the SD ($F_{1,16} = 4.194$, $p = .057$, $\eta_p^2 = .208$) and FE ($F_{1,16} = 4.236$, $p = .056$, $\eta_p^2 = .209$). When walking clockwise, SD values tended to be higher, being significantly different when negotiating the wide track with a solid surface (Fig. 2). Under this same condition, FE values tended to be lower than in the anti-clockwise condition.

On the wide walking track, both SD and MV values were significantly higher than on the narrow track. Pairwise comparisons showed that this task constraint affected SD values most when walking clockwise on the solid surface. In contrast, MV values were affected regardless of walking direction or surface properties (Fig. 2). Fuzzy Entropy values did not show any significant differences, whilst DFA values were significantly lower when participants walked on the wide track (Table 3). Specifically, DFA differences between widths were most evident when participants walked on the solid surface (Fig. 2).

Finally, walking track surface seemed to influence both performance variables. Surface properties did not have a significant effect on SD values (Table 3), in the clockwise direction when walking on the wide track. However, SD values decreased when the walking surface was solid (Fig. 2). There were significant differences in MV values, regardless of track direction and width (Fig. 2). Higher values of MV emerged when walking on the foam surface (Table 3). Concerning the nonlinear performance measures, FE values were significantly higher in the foam conditions, although these differences were only displayed when participants walked in the anti-clock wise direction, on the wide track (Fig. 2). Detrended Fluctuation Analysis measures did not show any statistically significant differences in any conditions (Table 3).

When effects of all interacting constraints were analysed, Pearson Product Moment Correlation coefficients were computed in order to assess the relationship between gait performance (SD and MV variables) and the structure of variability (FE and DFA) (Table 4). Both performance variables were not significantly correlated with each other, meaning that they contributed different information about walking performance. Regarding the structure of movement variability, SD values were negatively correlated with FE and positively related to DFA. The MV measure showed the opposite relationship (positively related to FE and negatively related to DFA). These relationships were not statistically significantly correlated under all interacting conditions.

Table 2
Average values (mean ± SD) in each walking condition of every variable calculated in the study.

Walk track	*SD*	*MV*	*FE*	*DFA*
Anti-Clockwise				
Narrow foamed	2.35 ± .57	0.337 ± .08	0.516 ± .15	1.21 ± .22
Narrow solid	2.22 ± .51	0.288 ± .08	0.461 ± .16	1.28 ± .13
Wide foamed	2.68 ± .70	0.395 ± .12	0.524 ± .16	1.13 ± .10
Wide solid	2.43 ± .48	0.346 ± .08	0.488 ± .13	1.14 ± .14
Clockwise				
Narrow foamed	2.34 ± .52	0.332 ± .11	0.500 ± .15	1.22 ± .22
Narrow solid	2.28 ± .51	0.291 ± .10	0.453 ± .17	1.27 ± .18
Wide foamed	2.72 ± .68	0.375 ± .11	0.488 ± .16	1.14 ± .13
Wide solid	2.60 ± .50	0.358 ± .10	0.471 ± .14	1.17 ± .15

Note. SD = Standard Deviation; MV = Mean Velocity; FE: Fuzzy Entropy; DFA = Detrended Fluctuation Analysis. Units of SD are in cm; Units of MV are in cm/s.

Table 3
Repeated measures ANOVA for all variable to see the overall effect of all constraints.

	Direction			*Track*			*Surface*		
	F	Sig	η_p^2	F	Sig	η_p^2	F	Sig	η_p^2
SD	4.194	.057	.208	**6.910**	**.018**	.302	3.086	.098	.162
MV	.014	.909	.001	**29.092**	**< .001**	.645	**9.121**	**.008**	.363
FE	4.236	.056	.209	.510	.486	.031	**7.309**	**.016**	.314
DFA	.379	.547	.023	**7.571**	**.014**	.321	4.420	.052	.216

Significant values are indicated in the table. 'F' values and significant values are marked in bold when $p < .05$.

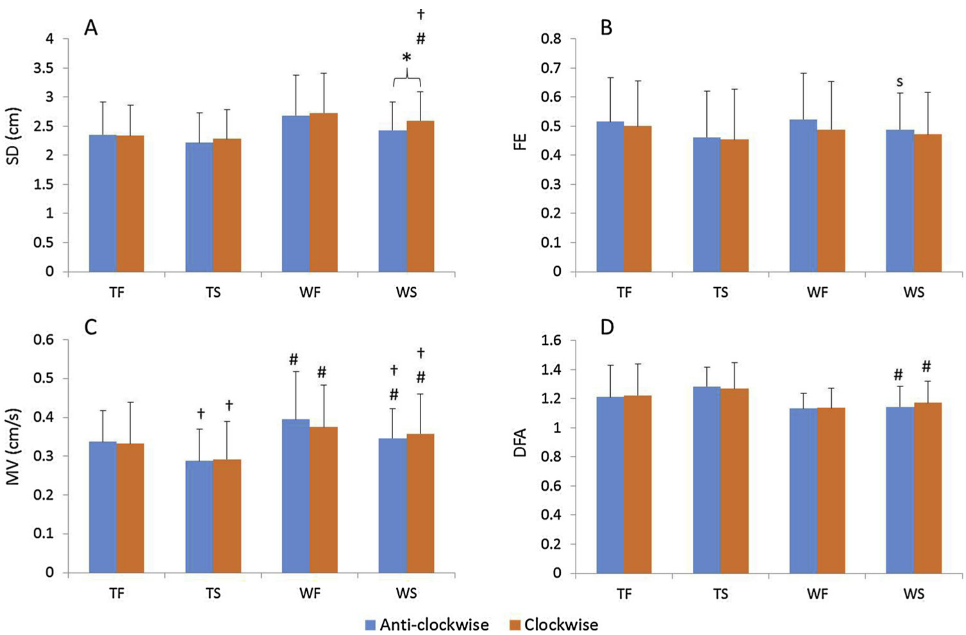

Fig. 2. Pairwise Comparisons between direction of walking, width of the track and surface of the track in all variables: A) SD = Standard Deviation; B) FE = Fuzzy Entropy; C) MV = Mean Velocity; and D) DFA = Detrended Fluctuation Analysis; NF = narrow foam; NS = narrow solid; WF = wide foam; WS = wide solid.
* = significant differences between the two different directions of the track; # = significant differences between the two different widths of track; † = significant differences between the two different surfaces of track.

Table 4
Pearson product moment correlation coefficient calculated between performance variables and nonlinear variables in each walking condition.

	MV	FE	DFA		MV	FE	DFA
Anti-clockwise							
NF				**NS**			
SD	.132	**−.603***	**.517***	SD	−.006	**−.600****	.073
MV		**.703****	−.063	MV		**.780****	−.444
FE			−.451	FE			−.451
WF				**WS**			
SD	.155	**−.544****	.146	SD	.004	**−.643****	**.669****
MV		**.689****	−.344	MV		**.752****	−.390
FE			**−.488***	FE			**−.674****
Clockwise							
NF				**NS**			
SD	.354	−.324	.418	SD	−.114	**−.650****	.094
MV		**.751****	**−.545***	MV		**.811****	**−.539***
FE			**−.797****	FE			**−.518***
WF				**WS**			
SD	−.227	**−.670****	.237	SD	−.264	**−.722****	.289
MV		**.823****	**−.678****	MV		**.832****	**−.654****
FE			**−.685****	FE			**−.652****

SD = Standard deviation; MV = Mean Velocity; FE = Fuzzy Entropy; DFA = Detrended Fluctuation Analysis.
N = narrow track; W = wide track; F = foam surface; S = solid surface.
** $p < .01$.
* $p < .05$.

4. Discussion

Previous studies have argued that re-organisation of motor system DoFs depends on interactions between system intrinsic dynamics (coordination tendencies of individuals) and performance task constraints [14]. These system adaptations seem to reflect increases and decreases in motor pattern variability. Previously, we have highlighted how participants modify their postural control dynamics according to different constraints, particularly task difficulty and availability of biofeedback [2]. Results showed that FE reduced and DFA increased as task difficulty level increased in the presence of biofeedback. However, when biofeedback was unavailable, the opposite trend in FE and DFA values was observed. Additionally, higher FE and lower DFA values were observed when biofeedback was available, rather than not. Regardless, performance was related to the structure of the motor variability. Few studies have addressed this relationship in dynamic balance tasks, such as during locomotion. For example, variability has been associated to balance deficits during walking [8] providing insights on neuromotor performance regulation [6]. Nevertheless, most studies of gait variability have focused only on magnitude, and not time-dependent structure [24].

Here, we sought to understand whether manipulation of task constraints would result in changes in the magnitude or structure of motor system variability observed in a basic walking task. We also investigated the relationship between performance in achieving task goals and the structure of motor variability. Three different constraints were manipulated during the experiment: walking direction, track width and surface properties.

The metronomic rhythm used was constant along all the trials, standardizing the possible effect it could cause. Knowing that performance in preferred conditions can lead to more irregular and less autocorrelated behaviours [24], the authors chose 130 bpm as metronomic rhythm in order to keep a cadence fast enough to be far from the preferred cadence of any participant.

Although the majority of participants were right-limb dominant, they did not display significant changes in their variability during task performance regarding the walking direction. However, the trend seems to indicate that the fluctuations were bigger and more regular in clock-wise conditions. Recent studies have provided clear evidence for a leftward (anti-clockwise) turning preference in right-handers, while non-right-handers show a bias towards the opposite turning direction (clockwise) [19]. Since most of the participants were right-limb dominant, the trend we found would support the findings in the literature, performance in preferred conditions can lead to more irregular and less auto-correlated behaviours [24].

Participants displayed lower SD and MV values when walking on the narrower track. This observation indicates that, because of the increased stability challenge this width implies, less variable and slower movements emerged in the narrower track condition. The need to maintain the centre of mass lateral displacement inside a narrower track may have constrained their movements, and the structure of movement variability, with more auto-correlated movement (increase in the DFA values) being observed. However, similar movement regularity (FE) was recorded on the narrow walking track. The greater amount of auto-correlation displayed on the narrow walkway could indicate a reduction in the number of adjustments performed by participants [28], made without stepping outside the track. These observations imply that this task constraint caused a reduction in the number of available solutions to achieve the task goal. This restriction on the available solutions is reflected in the decrease of MV and DFA.

The foam surface was also associated with an increase in the amplitude and velocity of movement adaptations made. It is apparent that SD values changed significantly only during performance in the clockwise direction and on the wide walking track, being higher on the foam surface than on the solid surface. However, MV values were significantly lower when participants walked on the solid surface, regardless of the track direction and width. A possible reason for the increase in the magnitude of variability (SD) and movement velocity is that participants may have used it as part of a strategy for acquiring useful information from the environment to achieve their task goal [1,29].

This idea would be supported by the fact that all the observed statistically significant differences were greater when walking on the solid surface. It is possible that, when walking on the foam surface, participants increased their movement variability (evidenced by higher SD values) and their movement velocity (higher MV), to create more information during performance to achieve the task goal, regardless of the width of the track. This can be related to the phenomenon referred as “sensory reweighting”. Depending on environmental conditions, the relative contribution of each sensory system changes to achieve an appropriate adaptation [30]. During gait, the plantar sole of the foot detects changing pressure patterns which provide important information about the disposition and movement of the body’s centre of mass [17]. Walking on foam surfaces may mask this capacity, decreasing the information provided by the environment (i.e. the floor). In order to enhance the information to control ankle movements and perform the task, participants may have had to increase their variability (SD) when they were walking on the foam surface. According to Davids, Glazier [1], this increase in movement variability can enhance perception of information to support motor performance. This exploratory process varies substantially from individual to individual and from task to task. This implies that the foam surface forced participants to increase their movement variability (SD) and movement velocity in order to perceive rich information to regulate their movements during task performance.

With regard to the structure of movement variability, on the foam surface FE mean values were higher. These differences were more clearly displayed when walking in the anti-clockwise condition and on the wide walking track.

The correlational analysis found that larger movement fluctuations are related to the structure of kinematic variability, with less irregularity and greater auto-correlations. On the other hand, the higher velocity in gait movements was related to greater irregularity and lower autocorrelation in the kinematic variability structure. These findings are aligned with results of previous studies [14], and are harmonious with findings from our study on static balance [2]. Taken together, these studies reveal that a specific relationship emerges between system variability structure and movement performance, which is dependent on task constraints and can be observed in different types of balance tasks: static and dynamic.

In conclusion, this study suggests that specific task constraints lead to changes in the magnitude and structure of motor variability observed in locomotion. Specifically, the direction of walking has no effect on variability. However, the width and the compliance of the track changed both characteristics of variability. A narrower track reduced SD and MV and increased auto-correlation, suggesting a reduction in the number of available solutions to achieve the task goal. Conversely, a foam surface caused an increase in SD and MV, with higher values of FE. These results could be related to an exploratory strategy, of increased variability in order to enhance information perception.

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