COORDINATION VARIABILITY DURING OVERGROUND, TREADMILL AND TREADMILL-ON-DEMAND RUNNING

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The purpose of this study was to investigate differences in lower extremity coordination variability between overground, treadmill and treadmill-on-demand running. A modified normalised root mean square difference technique was used to quantify the variability in lower extremity coordination calculated from the kinematic data collected during ten strides of overground, treadmill and treadmill-on-demand running at 3.5 m.s^{-1}. Although no significant differences were observed between the two types of treadmill, significantly reduced ($p < 0.02$) coordination variability was seen in the treadmill and treadmill-on-demand conditions compared to overground locomotion. Therefore, a constant belt speed during treadmill locomotion does not account for the differences seen between overground and treadmill running and further work is required to determine factors that cause the difference.

KEY WORDS: treadmill-on-demand, overground, running, treadmill, coordination, variability

INTRODUCTION: Biomechanics researchers have recently employed analysis techniques from the dynamical systems approach to movement coordination and control to address a range of research questions in the study of locomotion (e.g. Hamill *et al.*, 1999; Field-Fote and Tepavac, 2002; Ferber *et al.*, 2005). This approach affords a positive functional role to movement variability, as opposed to the traditional association of variability with error. A related influence of the dynamical systems approach is the notion that the coordination or coupling between joints is important. Examples of studies that have employed dynamical systems methods in biomechanics include investigations into the relationship between coordination variability and joint pain (Hamill *et al.*, 1999), the effect of orthoses on coordination and coordination variability (Ferber *et al.*, 2005) and the relationship between spinal cord injury and coordination variability (Field-Fote and Tepavac, 2002). Some of these studies were conducted overground (Ferber *et al.*, 2005) whilst others involved treadmill locomotion (Hamill *et al.*, 1999; Field-Fote and Tepavac, 2002).
Obviously, an implicit assumption of the studies in which a treadmill was used was that treadmill locomotion simulates overground locomotion effectively in terms of coordination variability. Wheat *et al.* (2003) presented evidence that questions this assumption. We reported that treadmill running was associated with significantly lower coordination variability than overground running for two of the three joint couplings studied. The results were in agreement with data presented by Dingwell *et al.* (2001) who studied differences in the variability in kinematics between overground and treadmill walking. Similar to Dingwell *et al.* (2001), Wheat *et al.* (2003) suggested that the decreased coordination variability could be due to the treadmill belt imposing an artificially constant speed, externally driving the participant's feet throughout the stance phase of each stride cycle.
Minetti *et al.* (2003) recently reported details of an innovative treadmill design in which the speed of the treadmill belt is dynamically controlled via an interface with an ultra-sonic range detector. During locomotion on the 'treadmill-on-demand' the belt speed is continuously changed according to the participant's desire to accelerate, decelerate or keep a constant speed (Minetti *et al.*, 2003). Consequently, coordination variability measured on the treadmill-on-demand might better resemble that measured overground than the conventional treadmill. Therefore, the purpose of this study was to compare coordination variability measured during running overground, on a conventional treadmill and on the treadmill-on-demand. We

hypothesised that coordination variability measured during treadmill-on-demand running would more closely resemble that measured overground than on the conventional treadmill.

METHODS: Twelve male participants were recruited to take part in the study and all completed testing. *A priori* power calculations (α = 0.05, β = 0.20) based on the data presented by Wheat *et al.* (2003) indicated that this number of participants gave the study sufficient power to detect differences between overground treadmill and treadmill-on-demand conditions. Participants had an average (± SD) age of 23.4 ± 4.2 years, height of 1.80 ± 0.07 m and body mass of 74.4 ± 7.9 kg. The Local Research Ethics Committee approved the procedures, and written informed consent was gained from each participant before data collection. Pre-moulded, Velcro backed thermoplastic shells, equipped with four 12.5 mm retro-reflective markers, were attached to the participant's left shank and thigh using the technique described as 'optimal' by Manal *et al.* (2000). Additionally, eight further retro-reflective markers were attached to the participant's pelvis and right foot at relevant anatomical landmarks.
Prior to data collection, participants – who were experienced treadmill runners - completed a 10 minute habituation period on the treadmill-on-demand. All kinematic data were collected using a nine camera motion capture system (VICON, Oxford Metrics, Oxford, UK), sampling at 120 Hz. In the overground condition, participants were required to complete 10 'good' running trials at 3.5 $m.s^{-1}$ (± 5%). A trial was accepted if a full right foot stride occurred within the measurement volume, without any obvious alterations to running stride, while running at the desired speed. The procedures for the treadmill and treadmill-on-demand trials were identical; participants were required to run at 3.5 $m.s^{-1}$ on the treadmill for one minute, at the end of which 15 s of kinematic data containing at least 11 right foot strikes were collected. As running speed was not fixed during the treadmill-on-demand trials, similar to the overground condition, a ± 5% boundary of acceptable speeds was used.
The raw three-dimensional coordinate data were filtered using generalised cross-validated quintic splines. Subsequently, three-dimensional Joint Coordinate System angles were calculated at the ankle, knee and hip joints using MARey Software (Cavanagh *et al.*, 2001) written for MATLAB (Natick, MA, USA). The angular displacement profiles for each trial were cropped to the length of a right leg stride using the marker data and then interpolated to 101 data points using a cubic spline procedure. Variability in coordination over the ten strides in each condition was quantified using a modified version of the normalised root-mean square difference (mNoRMS) method introduced by Sidaway *et al.* (1995). The modification ensured that a measure of variability could be obtained for every data point throughout the stride. In addition to calculating the average mNoRMS value across the entire stride, average mNoRMS values were also calculated within specific intervals of the stride. Coordination variability was calculated for the following inter-joint couplings: hip flexion/knee flexion, hip flexion/ankle dorsiflexion and knee flexion/rearfoot inversion. A series of two-factor (mode, interval) analyses of variance (ANOVA), with repeated measures on both factors were performed for each joint coupling to assess differences between the modes of running. The alpha level of significance was adapted using the Bonferroni technique to reduce the risk of a type I family-wise error (α = 0.05/3 = 0.02) and paired *t*-tests were used *post-hoc*. Also, results of the inferential tests were supplemented with effect size statistics in an attempt to quantify the meaningfulness of the differences – Cohen's (1988) criteria was used in which 0.2, 0.4 and 0.8 are small, medium and large effects respectively.

RESULTS: The average mNoRMS values for each joint coupling, during each mode of running, are given in Table 1. Significant main effects for the mode factor were seen for all joint couplings ($p < 0.02$). Coordination variability was significantly greater in the overground condition compared to the treadmill and treadmill-on-demand conditions during the swing phase and various intervals of stance for all couplings (see Table 1). Effect size statistics indicated that, based on Cohen's (1988) criteria, these differences were large (range: 0.80-1.61). For all joint couplings, during all phases of the stride, no significant differences ($p>0.02$)

were reported between the treadmill and treadmill-on-demand conditions (effect size range: 0.11-0.44).

Table 1 Average (± SD) mNoRMS values for the three joint couplings over the entire stride and different intervals of the stride in the overground (OG), treadmill (TM) and treadmill-on-demand (DE) conditions

		mNoRMS (°)					
		Stride	**Swing**	**0-25% Stance**	**26-50% Stance**	**51-75% Stance**	**76-100% Stance**
Hip Flexion/Knee Flexion	**OG**	$4.44^{*\#}$ ± 1.20	$5.22^{*\#}$ ± 1.48	$3.79^{*\#}$ ± 1.38	2.74 ± 1.06	$3.05^{\#}$ ± 1.22	$2.61^{*\#}$ ± 0.65
	TM	2.85^{*} ± 0.78	3.16^{*} ± 0.88	2.62^{*} ± 0.84	2.22 ± 0.72	2.28 ± 0.70	1.98^{*} ± 0.48
	DE	$2.85^{\#}$ ± 0.63	$3.36^{\#}$ ± 0.77	$2.42^{\#}$ ± 0.81	1.99 ± 0.68	$2.01^{\#}$ ± 0.45	$1.88^{\#}$ ± 0.44
Hip Flexion/ Ankle Dorsiflexion	**OG**	$3.31^{*\#}$ ± 0.85	$3.49^{*\#}$ ± 0.94	2.51^{*} ± 0.76	2.90^{*} ± 1.02	3.12^{*} ± 1.27	$3.45^{\#}$ ±1.11
	TM	2.12^{*} ± 0.51	2.1^{*} ± 0.48	1.87^{*} ± 0.71	2.05^{*} ± 0.74	2.1^{*} ± 0.71	2.59 ± 1.19
	DE	$2.24^{\#}$ ± 0.61	$2.23^{\#}$ ± 0.54	2.01 ±0.74	2.19 ± 1.54	2.33 ± 1.23	$2.42^{\#}$ ± 0.84
Knee flexion/ Rearfoot inversion	**OG**	$4.21^{*\#}$ ± 1.06	$4.96^{*\#}$ ± 1.33	$4.24^{*\#}$ ± 1.56	2.36 ± 0.71	2.45 ± 0.87	$2.58^{\#}$ ± 0.91
	TM	2.61^{*} ± 0.73	2.87^{*} ± 0.83	2.73^{*} ± 1.08	1.97 ± 0.65	1.86 ± 0.57	1.91 ± 0.38
	DE	$2.56^{\#}$ ± 0.72	$2.91^{\#}$ ± 0.77	$2.56^{\#}$ ± 0.97	2.09 ± 1.33	1.76 ± 0.69	$1.71^{\#}$ ± 0.31

$^{*\,\#}$ Significant difference between modes of locomotion ($p < 0.02$)

DISCUSSION: The purpose of this study was to compare coordination variability measured during overground, conventional treadmill and treadmill-on-demand running. In comparison to overground running, significantly reduced coordination variability was observed in the treadmill and treadmill-on-demand conditions, over the entire stride as well as various phases of the stride cycle, for all joint couplings. Even during the periods of the stride in which the differences between overground and the two treadmill conditions were non-significant, the pattern of increased coordination variability during overground running can be seen in all couplings (Table 1).

The decreased variability in lower extremity coordination during treadmill running seen in this study is consistent with previous investigations (Dingwell *et al.*, 2001; Wheat *et al.*, 2003). Wheat *et al.* (2003) reported lower variability in couplings of hip flexion-ankle dorsiflexion and knee flexion-rearfoot inversion during treadmill compared to overground running. Further, Dingwell *et al.* (2001) studied differences in the variability in kinematics during overground and treadmill walking and reported significantly reduced variability in sagittal plane ankle and knee angles during treadmill locomotion. Both Wheat *et al.* (2003) and Dingwell *et al.* (2001) suggested that a possible reason for the differences between overground and treadmill variability was the artificially constant speed of the treadmill belt, externally driving the participants' feet throughout the stance phase of the stride. Therefore, in the present investigation, we hypothesised that coordination variability measured on the treadmill-on-demand, in which the belt speed is not constant, would better resemble that measured overground than the conventional treadmill. However, the results of this investigation do not support this hypothesis as the differences between the treadmill-on-demand and conventional treadmill were non-significant ($p < 0.02$) and effect sizes were only small to moderate (0.11-0.44). Further, the results suggest that the constant speed of the treadmill

belt during conventional treadmill locomotion does not account for the differences in coordination variability seen between overground and treadmill running.
Various factors have been implicated as potential reasons for differences between overground and treadmill kinematics. Examples include differences in the mechanical characteristics of the treadmill and overground surfaces (Dingwell *et al.*, 2001) and reductions in air resistance experienced by the participants in the treadmill condition (van Ingen Schenau, 1980). However, there is no evidence in the literature to suggest what effects changes in these parameters might have on coordination variability. A viable explanation for the differences in coordination variability between the modes of locomotion is the altered perceptual information available during treadmill running. As van Ingen Schenau (1980) highlighted, during overground running the surroundings move with respect to the participant which is not the case during treadmill locomotion. An interesting direction for future research would be to evaluate the effects of introducing optical flow information, comparable to that in overground locomotion, into a treadmill running condition. All of the factors cited above were consistent across the treadmill and treadmill-on-demand conditions which might serve to explain why no significant differences were reported between these modes of locomotion.

CONCLUSION: The results of this study highlighted significantly reduced coordination variability during treadmill and treadmill-on-demand compared to overground running. Further, treadmill-on-demand running did not better resemble overground running in terms of coordination variability than the conventional treadmill. Additional work is required to determine causes for the consistent observation of decreased variability in treadmill compared to overground locomotion.

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