COORDINATIVE VARIABILITY IN FOREFOOT RUNNERS DURING AN EXHAUSTIVE RUN

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The purpose of this study was to investigate the effects of a prolonged run on coordinative variability and how it relates to impact dynamics in forefoot runners during an exhaustive run. Thirteen individuals ran on an instrumented treadmill and were instructed to select a pace they can maintain for at least 15 minutes but no longer than 20 minutes. A post hoc analysis revealed two subgroups emerged. Eight individuals were able to maintain a forefoot striking pattern throughout the run (NCG: no change group), while the remaining five moved to a more rearfoot strike (CG: change group). The results demonstrated that the impact characteristics changed for the CG only. This was accompanied by changes in CV, suggesting that individuals reorganize their degrees of freedom as they fatigue. The reorganization of footfall patterns may represent an adaptation to meet energy requirements to complete the task.

KEY WORDS: footfall patterns, dynamical systems

INTRODUCTION: In 2015, approximately 17 million runners crossed the finish line in U.S. running events, with 45% completing a 5km ("State of the Sport- U.S. Race Trends", 2015). With such a large number of individuals participating in recreational running, the causes of running related injuries have been the subject of a large portion of the research conducted in biomechanics. The role of footfall patterns in the development of these injuries has been of particular interest. An estimated 74.9-98.12% of runners use a rear foot (RF) footfall pattern (Valenzuela, Lynn, Mikelson, Noffal & Judelson 2015). Because of such a high prevalence, the majority of the information we know about running mechanics is from RF runners.

Over the recent years forefoot (FF) running has been considered to be a safer technique, compared to RF running, because of the absence of an impact peak and the lower loading rate (Jewell, Boyer & Hamill, 2017). Despite the widespread beliefs there is no conclusive evidence to show that there is a reduced risk of injury or improvements in running economy (Hamill & Gruber, 2017). Approximately 1.4 % of runners have been said to be true FF runners. Field observations show that the number of FF runners declines over the course of an endurance race, suggesting it is a difficult pattern to maintain as individuals fatigue (defined here as reduction of force producing capabilities) (Hasegawa, Yamauchi & Kraemer 2007; Jewell et al, 2017; Larson, Higgins, Kaminski, Decker, Preble, Lyons, McIntyre & Normile 2011). The adaptation may be metabolically linked given that RF strikers have been found to have a lower rate of carbohydrate oxidation compare to FF runners (Gruber, Umberger, Braun & Hamill (2013).

From a dynamical systems perspective, the transitions in footfall patterns may represent a context dependent adaptation. That is, to meet the task goals and the metabolic requirements the running pattern must change. To date, the majority of our understanding of changes in footfall patterns have largely come from a mechanical and physiological perspective and have not taken into consideration how the control of a complex movement changes over the course of an exhaustive run. To gain insights in to how control changes with fatigue, coordinative variability (CV) may be used as means of assessing the system’s flexibility (Hamill, Palmer & Van Emmerik, 2012). Therefore, the purpose of this study is to investigate the effects of a prolonged run on CV and how it relates to impact dynamics in forefoot runners during an exhaustive run. We hypothesized that as individuals fatigue footfall patterns will begin to resemble a more rear foot strike, resulting in increased coordination variability (Jewell et al, 2017). Fatigue will lead to a reduction in the peak vertical ground reaction force (VGRF) (i.e. the active peak) and an increase in the VGRF loading rate (indicative of a more RF striking pattern.)

METHODS: Thirteen healthy recreationally active runners participated in the study. All participants were habitual FF runners that ran at least 24 km per week and free from injury. To confirm a FF footfall pattern, plantar-flexion angles and VGRFs were assessed as they ran both overground and on a treadmill. During this screening period the participant's preferred speed was also assessed by asking them to run at a pace that reflected their previous races and/or training runs and that could be maintained for 15 min but not more than 20 min (Jewell et al, 2017). To assess the effects of fatigue, 3-D kinematic data were collected at 200 Hz using eight Pro-reflex cameras (Qualisys, Inc., Gothenburg, Sweden) for 15 seconds at the beginning and the end of the run (10% and 100%, respectively). Markers were placed on the right thigh, leg and foot (a multi-segment model) (Leardini, Benedetti, Berti, Bettinelli, Nativo & Giannini, 2007). Kinetic data were recorded at 1000 Hz using an instrumented treadmill (Treadmetrix, Park City, Utah). During the exhaustive run, a rating of perceived exertion (RPE) was collected. Kinematic data were filtered with a 12 Hz cutoff while analog channels from the force treadmill were filtered with a 30 Hz cutoff. All kinematic data were processed in Qualisys Tracking Manager (Qualisys, Inc., Gothenburg, Sweden) and exported to Visual3D (C-motion, Germantown, MD) for analysis.

A *post hoc* analysis of sagittal plane ankle angles at initial contact and VGRF revealed that two sub-groups emerged in our data set. Of the original 13 subjects, eight individuals did not display any changes in footfall patterns at the end of the run, referred to as No Change Group (NCG), whereas the remaining five participants demonstrated a decrease in ankle angle and the emergence of an impact peak, referred to as the Change Group (CG). The CG was composed of 4 males and 1 female (27 ± 10 years of age, height 1.7 ± 0.1 meters, mass 67 ± 9 Kg) that ran an average of 52.2 ± 15.5 Km per week. The NCG had 3 males and 5 females (25.4 ± 9 years of age, height 1.7 ± 0.1 meters, mass of 67.4 ± 8 Kg) that ran an average of 43.6 ± 19.1 Km per week. To assess kinetic changes over the course of the run, loading rate of the VGRF and peak force (normalized to bodyweight (BW)) were used. A modified vector coding technique was used to determine CV during early stance (Hamill et al., 2012). All of the analyses were conducted using 13 strides (Hafer & Boyer (2017). The following couplings were assessed: 1) leg (Z)/foot (Y); 2) thigh (X)/leg (X); and 3) thigh (X)/leg (Z) 4) forefoot (Y) / rearfoot (Y) where X, Y, Z represent flexion/extension, ab/adduction, and internal/external rotation, respectively (Hamill et al., 2012; Heiderscheit, 2002)

To assess the effects of fatigue, Wilcoxon signed rank tests were used to compare the first 1/3 of stance (i.e. weight acceptance phase) for the beginning and the end of the run for each of the following dependent variables: coordinative variability, loading rate, and peak force. A criterion alpha level of 0.05 was used.

RESULTS: During the experiment the CG ran at a speed of 4.0±0.5 m/s and ended their run with an RPE of 18.4±0.5 (began the run at 10.4 ± 2.3). The NCG ran at a speed of 3.6±0.5 m/s and ended their run with an RPE of 18.6 ± 0.5 (began the run at 9.8 ± 2.6). When comparing CV from the beginning to the end of the run, it increased in 3 out of 4 of CG's couplings and half of the NCG's couplings (Figure 1). As expected, the Loading Rate significantly increased for the CG but not the NCG, suggesting they maintained their FF strike pattern throughout the course of the run. There were no differences in Peak Force for either group (Table 1).

DISCUSSION: The purpose of this study was to investigate the effects of a prolonged run on CV and how it relates to impact dynamics in forefoot runners during an exhaustive run. The hypothesis that the peak vertical ground reaction force would decrease was not supported. Neither group saw changes in active peak forces (Table 1). As expected, the CG group saw significant increases in loading rate at the end of the run as a result of changing to the RF pattern, whereas the NCG did not; partially supporting the hypothesis that loading rate would increase with fatigue. This result is in line with previous literature that suggests that FF runners begin to move toward a RF running pattern as they fatigue.

Table 1
Mean ± SD for loading rate and peak force for the beginning and end of the run.

	Change Group		No Change Group	
	Loading Rate (BW)	Peak Force (BW)	Loading Rate (BW)	Peak Force (BW)
Beginning	55.65 (8.84)	2.54 (0.25)	43.58 (13.11)	2.65 (0.12)
End	82.17 (28.80)	2.56 (0.26)	44.28 (12.98)	2.61 (0.17)
P-value	0.043	0.89	0.575	0.263
Effect Size	1.24	0.077	0.053	0.27

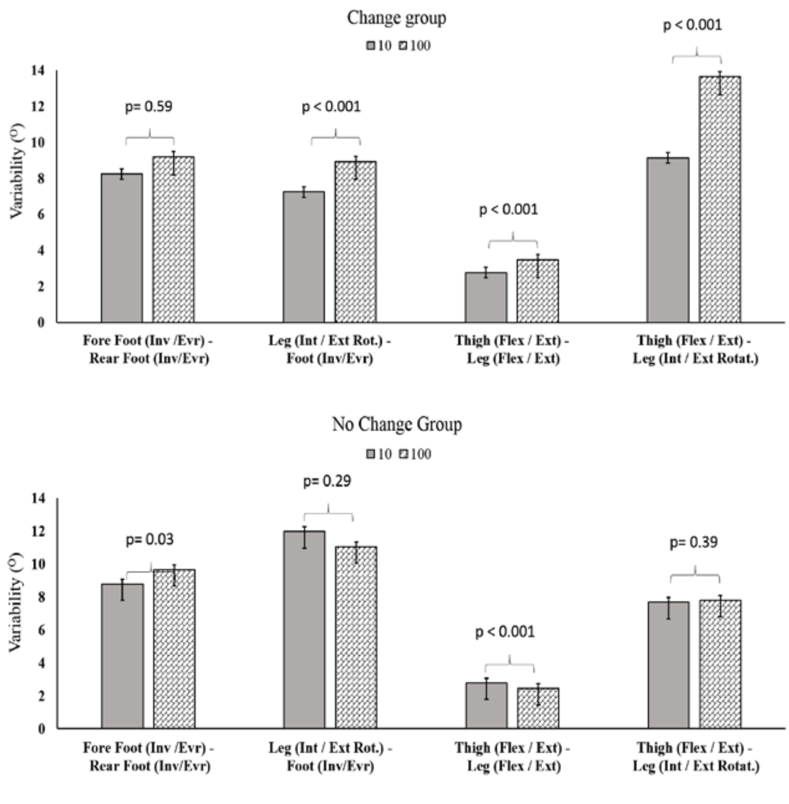

Figure 1. Coordinative variability for the weight acceptance phase of stance for the thigh-shank, leg-foot, and the forefoot-rearfoot at 10% and 100% of the run. (Note the bars correspond to the standard error of the mean).

From a traditional motor control perspective, some would argue that the increase in CV is indicative of a loss of control as people fatigue. The alternative interpretation from a dynamic systems perspective is that the change is a functional one, such that it represents a reorganization of the system's degrees of freedom to accomplish the goal of the task. This interpretation is supported by the work of Gruber and colleagues (2013) who showed the changes in the footfall pattern from FF to RF are accompanied by a reduction in carbohydrate consumption. The authors suggested the change in footfall pattern may be a means of delaying the onset of fatigue.

CONCLUSION: The results of the current study showed significant changes in CV along with changes in impact peak dynamics (in the CG group only). The effort of the participants throughout the run was similar in demand to a 5k event. The emergence of the impact peak in the CG group may represent a change in strategy from an active shock attenuation strategy (as seen in FF runner that maintain a plantar flexed foot at touchdown) to a more passive means of attenuating shock seen in RF running (Jewell et al., 2017). From a coaching perspective these findings are important because athletes who choose to run in a FF pattern, either by coaching or it's their natural pattern, should undergo a training regimen that will strengthen different muscle groupings involved in each of the footfall patterns. The strength training could potentially guard against any injury that may occur as a function of introducing new stresses on the lower limb soft tissue.

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