USE OF SELF-ORGANIZING MAPS TO STUDY SEX- AND SPEED-DEPENDENT CHANGES IN RUNNING BIOMECHANICS

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Self-organizing maps (SOM) are a type of artificial neural network for 1) clustering variables and visualizing large datasets and 2) quantifying coordination patterns. The purpose of this study was to use a SOM to investigate the effect of sex and speed on coordination patterns during running. Seventeen females and 15 males ran at their long-slow distance (LSD) training speed and at a speed 30% faster than LSD. Thirty-seven biomechanical variables (gait parameters, joint kinematics, coupling angle variability, EMG, and impact kinetics) were recorded and/or calculated, and analyzed with a SOM. The SOM analysis showed a significant shift in coordination pattern for males and females as running speed increased. This shift was characterized primarily by increases in the rate of ground reaction force loading, tibial impact shock, step lengths, and medial gastrocnemius muscle activation.

KEYWORDS: machine learning, neural network, sports, injury.

INTRODUCTION: In the U.S. alone there are about 62 million runners who run on a regular basis. In addition, there are about 18 million runners who participate in road races, and about 60% of them are females. Between 20-79% of runners get injured every year, and the rate of injuries has not changed in the past 30 years (Van Gent et al., 2007). Although females have higher rates of running related injury (RRI) than males (Taunton et al., 2002; Wright et al., 2015), not much is known about sex-specific differences in etiology of RRI.
Rate of loading (ROL) is considered as a risk factor for RRI, such as patellofemoral pain and tibial stress fracture (Davis et al., 2016). In addition, tibial impact shock (TIS) is associated with the development of RRI (Milner et al., 2006). Previous research on the effects of sex and speed on ROL found no significant differences between males and females (Keller et al., 1996). However, they used fixed absolute speeds, which may not reflect the impact kinetics that runners experience as they run most of their mileage. Therefore, not much is known about sex differences at individualized long slow distance speeds (LSD) i.e. the speed where runners log most of their mileage. In addition, the interaction effect between sex and speed for ROL and TIS is not well understood but may help elucidate sex-specific differences in the etiology of RRI. Females also demonstrate different muscle activation patterns (e.g., quadriceps dominance) than males during running and cutting tasks (Malinzak et al., 2001). Quadriceps activation patterns may also be associated with impact kinetics (Williams III et al., 2004). In addition, previous research suggests that movement variability is associated with overuse injury (Hamill et al., 1999), and it has been suggested that less movement variability at the hip/knee is associated with higher impact forces during running (Wang et al., 2018). However, there is a global lack of understanding about the influence of sex and running speed on the collection of impact kinetics, muscle activation patterns, and movement variability.
Self-organizing maps (SOM) have been used in gait studies to analyze large amounts of data and facilitate an understanding of complex movement patterns (Bartlett et al., 2014; Lamb et al., 2011). An SOM is a type of artificial neural network that 1) clusters variables and helps visualize patterns in large datasets and 2) quantifies coordination patterns. The purpose of this study was to use an SOM to investigate the effect of sex and speeds on biomechanical coordination patterns during running.

METHODS: Thirty-two healthy runners (17 females, 15 males, 22$\pm$3 years, 63$\pm$ 9 kg, 1.70 $\pm$.08 m), who ran at least ten miles per week and had no history of lower limb surgery and musculoskeletal or neuromuscular injuries in the past 6 months, were recruited for this study. All runners signed an IRB approved informed consent form before study participation. Participants warmed-up on a treadmill for 5 minutes, and then ran at their LSD speed for two minutes. Participants increased the speed by 15% for two minutes and then by 30% for two minutes of their LSD (LSD+30%). Thirty seconds of data were collected at each speed.

Kinematics of the lower extremities were collected with a motion capture system at 100 Hz (Vicon, Centennial, CO, USA). A tri-axial accelerometer was placed on the distal tibia to measure vertical acceleration at a frequency of 148 Hz (Delsys, Natick, MA, USA). An instrumented pressure treadmill (SciFit, Noraxon, Scottsdale, AZ, USA) was used to collect vertical ground reaction force (vGRF) at 100 Hz. Electromyography (EMG) sensors (Delsys, Natick, MA, USA) recorded activity from the gluteus medius (GM), vastus lateralis (VL), semitendinosus (ST), tibialis anterior (TA), and medial gastrocnemius (MG) at 1000 Hz.
A custom MATLAB (The Mathworks, Natick, MA, USA) program was used to process and filter kinematic data with a low-pass Butterworth filter at cutoff frequencies of 8 Hz. Low-pass Butterworth filters with cutoff frequencies of 13 Hz and 60 Hz were used to filter kinetic and acceleration, respectively. EMG of GM, VL, ST, TA, and MG were detrended, rectified, band-pass filtered (40-400 Hz). Lower extremity joint angles were calculated with Visual3D (C-Motion, In, Rockville, MD, USA). Vector coding was used to quantify movement variability and movement pattern proportions (Chang et al., 2008; Sparrow et al., 1987). Coupling angle (CA) variability of hip sagittal / knee sagittal plane and hip frontal / knee sagittal plane were calculated for each coupling at initial contact, mid-stance, late stance, and across the full stride cycle. Movement patterns were quantified by dividing the CA values into eight distinct patterns that represent the direction of motion (Chang et al., 2008). For example, the hip sagittal / knee sagittal plane CA were divided into hip flexion / knee flexion, hip extension / knee extension, hip flexion / knee extension, hip extension / knee flexion, hip flexion, hip extension, knee flexion, and knee extension. ROL was calculated as the peak vGRF derivative and normalized to body mass. TIS was calculated as the peak positive vertical acceleration during the early phase of stance.
Thirty-seven variables from all 32 runners and at two different speeds (i.e. LSD and LSD+30%) were used to construct a 64*37 (2 speeds x 32 runners * 37 variables) matrix, which was used to train the SOM (Kohonen, 2001). The Davies-Bouldin index was used to calculate the appropriate number of coordination patterns (through k-means clustering). To quantify the shift in coordination patterns of males and females across speeds, the Stuart-Maxwell test was used as a marginal homogeneity test for non-parametric nominal data. SOM weight planes were constructed to allow for visual inspection of how the 37 variables of interest (e.g., ROL and TIS) mapped onto the SOM. Hit histograms were added to the weight planes to show the locations of, and shifts in, individual trials on the SOM.

RESULTS: LSD and LSD+30% running speeds were 2.93±0.48 m/s and 3.80±0.62 m/s, respectively. The Davis-Bouldin test indicated a four cluster solution to the SOM (Figure 1). The Stuart-Maxwell test showed a significant shift between clusters for males (p = 0.029) and females (p = 0.007) as speed increased from LSD to LSD+30% (Table 1). Inspection of the contingency tables showed a general speed-dependent shift of trials into cluster 3. The shift of trials appeared to come from a decrease of trials in clusters 1 and 4 for both males and females. The shift in trials was supported by inspection of the hit histograms that were overlaid onto the SOM (Figure 2).

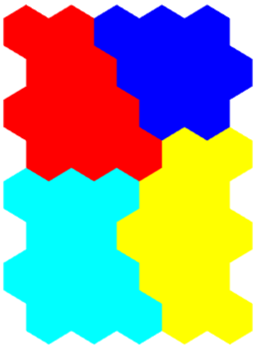

Figure 1: k-means clustering showing four clusters. Red = cluster 1 (top left), blue = cluster 2 (top right), cyan = cluster 3 (bottom left), yellow = cluster 4 (bottom right).

Table 1: Contingency tables for males (left) and females (right) counts

Males		LSD+30% 1	2	3	4	Total
LSD	1	1	0	3	0	**4**
	2	1	2	0	0	**3**
	3	0	0	1	0	**1**
	4	0	0	5	2	**7**
	Total	**2**	**2**	**9**	**2**	

Females		LSD+30% 1	2	3	4	Total
LSD	1	2	0	4	0	**6**
	2	3	0	1	1	**5**
	3	0	0	0	0	**0**
	4	0	0	4	2	**6**
	Total	**5**	**0**	**9**	**3**	

DISCUSSION: The purpose of this study was to use a SOM to investigate the effect of sex and speed on biomechanical coordination patterns during running. The k-means clustering solution of the SOM suggested the presence of four distinct coordination patterns. In addition, the Stuart-Maxwell test showed that there was a significant shift between coordination patterns (i.e., clusters) as running speed increased. Investigation of the hit histograms showed that at LSD speed most trials mapped onto clusters 1 and 4, whereas at LSD+30% speed some trials shifted and mapped onto cluster 3. Although this shift appeared consistent for both males and females, the changes in nominal frequency distributions that occurred with an increase in running speed were more significant in females than in males. However, the implications of the difference in associated *p*-values are not immediately apparent.

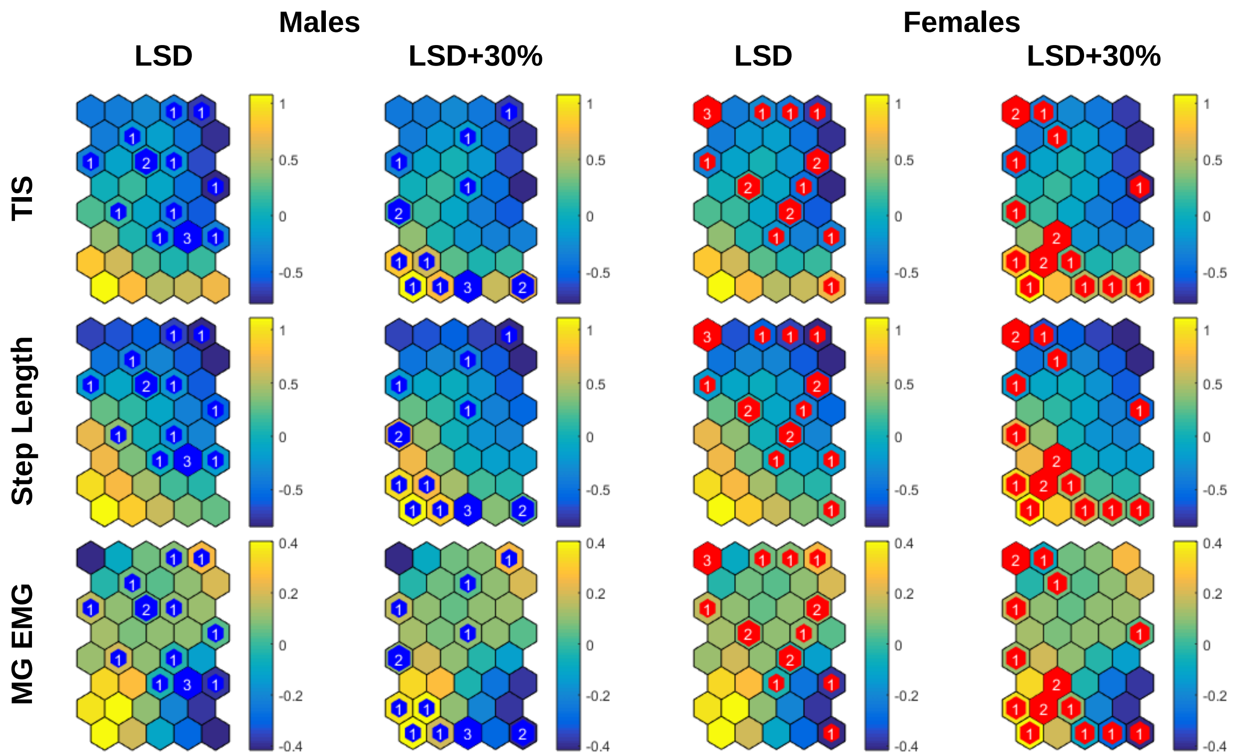

Figure 2: SOM weight planes for tibial impact shock (TIS: top row), step length (middle row), and medial gastrocnemius EMG (MG EMG: bottom row). Hit histograms are displayed as hexagons that reflect the number of mapped trials for males (blue; left two columns) and females (red; right two columns) at LSD (first and third column) and LSD+30% (second and fourth column) speeds. The colorbars indicate the z-score of each variable.

Visual inspection of the z-score color gradient of the weight planes showed that cluster 3 was characterized by relatively higher ROL, TIS, step length, and MG EMG than clusters 1 and 4 (Figure 2). It therefore appears that as speed increased both males and females shifted toward a running pattern characterized by higher magnitudes of impact kinetics, longer strides, and greater MG activation. A speed-dependent increase in TIS corroborates the work by Sheerin and colleagues (Sheerin et al., 2018), who reported a moderate correlation between running velocity and resultant tibial acceleration across speeds of 2.7-3.7 m/s. It is likely that the greater TIS and ROL are linked to the longer step lengths. As Stewart Maxwell test showed a shift from cluster 1 and 4 to cluster 3 as the running speed increased, it might important to focused on the variables that differentiate cluster 3 form cluster 1 and 4 and these were determined by visual inspection of weight planes graphs.

CONCLUSION: The results suggest a significant shift in the biomechanical coordination pattern of males and females as running speed increased from LSD to LSD+30%. This shift was characterized by an increase in ROL, TIS, step length, and MG EMG. Given that ROL and TIS may contribute to the development of RRI, the risk of RRI may also increase as running speed increases. However, a lack of significant differences in speed-dependent cluster shifts between males and females suggests that these changes occur to a similar extent in both sexes as they increase their running speeds.

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