EFFECTS OF HABITUAL FOOT STRIKE PATTERNS ON ANKLE MUSCLES ACTIVATION DURING RUNNING

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This study aimed to determine differences in muscle activation between habitual rearfoot strike pattern (RFS) and non-rearfoot strike pattern (NRFS) runners. Ten habitual RFS and ten habitual NRFS runners were recruited in this study. The electromyography signals were collected from the tibialis anterior, soleus, medial and lateral gastrocnemius muscles at 9 km/h running. The root mean square of each muscle and the co-activation of ankle flexors and extensors (CO_{Ankle}) were calculated. Independent *t*-tests or nonparametric tests were used to examine the differences between two groups. The results showed that during the pre-activation and swing phases, the CO_{Ankle} of RFS runners were greater than those of NRFS runners. This suggested that RFS runners with higher CO_{Ankle} at pre-activation might be a strategy in response to great impact force during the early of stance.

KEYWORDS: foot strike pattern, running, electromyography, muscle co-activation

INTRODUCTION: Running is one of the most popular sports in the world. With the popularity of running and the breaking of records in road events in recent years, there has been an increase in foot strike pattern related research. (Bovalino & Kingsley, 2021) reported that nearly 86% runners run with the rearfoot strike pattern (RFS).

There have been many studies reported the differences between the non-rearfoot strike pattern (NRFS) runners and RFS runners in kinematics, kinetics of lower extremity. During the initial contact, the RFS runners typically tends to exhibit a dorsiflexed and knee-flexed posture, while the NRFS runners typically tends to exhibit a plantarflexed and knee-flexed posture (Xu et al., 2021). At the same time, RFS runners have higher ankle stiffness, greater peak impact force (Xu et al., 2021). Besides, compared to RFS runners, NRFS runners have lower or even visually no the first peak vertical GRF(Boyer, Rooney, & Derrick, 2014). Considering that muscle activity has an impact on kinematics and kinetics, the study of muscle activation in different habitual foot strike patterns may provide information on foot strike patterns. Compared RFS runners, NRFS runners had greater RMS of medial gastrocnemius (MG), lateral gastrocnemius (LG), and lower RMS of tibialis anterior (TA) during the early of stance (Ahn, Brayton, Bhatia, & Martin, 2014). Apart from root mean square (RMS), co-activation is also important, but is seldom observed. Different RMS between two foot strike pattern, which might implied different co-activation modes between two foot strike patterns.

Therefore, this study aimed to determine differences in muscle activation between two habitual foot strike patterns. We hypothesized that: compared to RFS runners, (1) the activation of the TA in NRFS runners was lower at the end of the swing phase and early in the stance phase; (2) the activation of the MG, LG and soleus (SOL) in NRFS runners was higher at the pre-activation and the post-activation of stance; and (3) the agonist-antagonist co-activation of ankle flexors and extensors (CO_{Ankle}) in NRFS runners was lower at the end of the swing phase and early in the stance phase.

METHODS: Ten male RFS runners and ten male NRFS runners were included in this study (Table 1). The inclusion criteria were as follow: (1) consistently running more than 20km per week, (2) having no lower limb-related injuries and no neurological or cardiorespiratory diseases over the last three months, (3) having kept the habitual foot strike pattern for at least one year. Kinematic data were used to classify foot strike patterns in runners. RFS was considered when the foot strike angle was >8°, NRFS was considered when the foot strike angle was <8° (Altman & Davis, 2012).

Table 1: Basic information of participants.

Group	Age (years)	Height (cm)	Weight (kg)	Foot strike angle (°)
RFS (n=10)	33.40±7.15	173.00±6.20	65.62±6.00	**13.00±5.37***
NRFS (n=10)	35.20±9.60	172.10±3.81	70.44±8.70	**-4.25±3.85***
p	0.334	0.250	0.424	**0.000**

RFS: rearfoot strike pattern; NRFS: non-rearfoot strike pattern.

Experimental Protocols: Firstly, subjects warmed up on the treadmill at a self-selected speed for 5 minutes and changed to experimental clothing and cushioned running shoes. Then, bipolar surface EMG electrodes were attached to the muscle bally of TA, SOL, MG, and LG muscles of the left leg. Reflective markers were attached to the subject's heel, the first and fifth metatarsal head, the first toe. Additionally, rigid bodies with three non-co-linear reflective markers were adhered to the lateral aspects of the shank. After that, subjects were asked to run with the habitual foot strike pattern at 9km/h on the split-belt three-dimensional instrumented treadmill (1000Hz, Bertec Corporation, Columbus, OH, USA). Surface EMG (2000 Hz, Noraxon, Arizona, USA) was used to measure the activity of TA, SOL, MG, and LG. Vicon motion capture system (200Hz, Vicon, Oxfordshire, UK) was used to capture the trajectory of markers for calculating the subject's habitual foot strike pattern through foot strike angle. The data acquisition was started when the subjects' foot strike pattern was stabilized.
Data Processing: The EMG data of five steps of were analyzed for each participant, and the EMG signals were filtered using a second-order Butterworth band-pass filter from 20 to 400 Hz. After rectification, the signals were peak normalized with a sliding window of 100 ms. The stride cycle was defined as the instantaneous GRF at the initial contact to be >30N and the instantaneous GRF when taking off to <30N measured by split-belt three-dimensional instrumented treadmill. Then, the RMS of the target muscles was calculated in the stride cycle, the stand phase, the swing phase, the pre-activation (50 ms before initial contact), and the post-activation (50 ms after initial contact):

$$RMS = \sqrt{\frac{1}{T}\int_{t}^{t+T} EMG^2(t) \cdot dt}$$

where t is the start point of EMG signal, and $t + T$ is the end point of EMG signal. Based on the RMS, the ankle muscles co-activation ratio (CO_{Ankle}) was calculated as below:

$$CO_{Ankle} = \frac{RMS_{TA}}{(RMS_{SOL} + RMS_{MG} + RMS_{LG})/3}$$

Go (2018) found that the mechanical delay of the lower limb muscles was roughly 36 ms, which compared to the gait cycle duration was too short, so we did not consider this.
The kinematic data were filtered by a Butterworth fourth-order, low-pass filter at a 7 Hz cut-off frequency in V3D v5 (C-Motion, Maryland, USA), and the foot strike angle, which determined the foot strike pattern, was defined as the angle between the ground and the line connecting the first metatarsophalangeal joint and the heel reflective markers.
Statistical Analysis: Statistical analysis was performed using the software SPSS v26 (IBM Statistics, Chicago, USA). The Shapiro-Wilk test was used to determine whether the data conformed to normal distribution. For a normally distributed continuous variable, independent *t*-tests were performed between the two groups; for variables that did not conform to a normal distribution, the nonparametric independent samples test was performed. The level of significance was set at 0.05.

RESULTS: RFS runners exhibited a significantly greater foot strike angle than NRFS runners ($p < 0.05$, Table 1), and both groups maintained their habitual foot strike patterns when running. During the pre-activation and swing phases, the CO_{Ankle} of RFS runners were greater than those of NRFS runners ($p < 0.05$, Figure 1). And there were no significant differences for CO_{Ankle} in other phase and RMS of two foot strike patterns (Table 2).

Table 2: Muscle activation between different foot strike patterns.

Phase	Variables	RFS (n=10)	NRFS(n=10)	*p*-value
Stance	RMS_{TA}	0.46±0.10	0.46±0.18	0.090
	RMS_{SOL}	0.62±0.19	0.73±0.09	0.199
	RMS_{MG}	0.67±0.10	0.59±0.18	0.082
	RMS_{LG}	0.65±0.12	0.59±0.18	0.252
	CO_{Ankle}	0.72±0.17	0.73±0.31	0.060
Swing	RMS_{TA}	0.58±0.25	0.44±0.17	0.522
	RMS_{SOL}	0.14±0.16	0.18±0.08	0.226
	RMS_{MG}	0.14±0.06	0.25±0.08	0.194
	RMS_{LG}	0.17±0.17	0.29±0.34	0.151
	CO_{Ankle}	**4.21±2.78***	**1.76±0.92***	**0.043**
Stride Cycle	RMS_{TA}	0.57±0.13	0.47±0.11	0.587
	RMS_{SOL}	0.45±0.08	0.43±0.07	0.631
	RMS_{MG}	0.43±0.07	0.46±0.06	0.361
	RMS_{LG}	0.47±0.10	0.45±0.12	0.741
	CO_{Ankle}	1.29±0.34	1.08±0.27	0.961
Pre-activation	RMS_{TA}	0.49±0.24	0.56±0.18	0.247
	RMS_{SOL}	0.38±0.60	0.48±0.16	0.545
	RMS_{MG}	0.33±0.19	0.55±0.25	0.247
	RMS_{LG}	0.44±0.32	0.59±0.25	0.707
	CO_{Ankle}	**1.53±1.04***	**1.12±0.41***	**0.014**
Post-activation	RMS_{TA}	0.46±0.25	0.58±0.29	0.764
	RMS_{SOL}	0.67±0.31	0.86±0.25	0.381
	RMS_{MG}	0.69±0.30	0.70±0.26	0.840
	RMS_{LG}	0.65±0.12	0.59±0.18	0.567
	CO_{Ankle}	0.47±0.91	0.48±0.16	0.450

Note: *Indicates $p < 0.05$
RFS: rearfoot strike pattern; NRFS: non-rearfoot strike pattern; RMS: root mean square; CO: co-activation; TA: tibialis anterior; SOL: soleus; MG: medial gastrocnemius; LG: lateral gastrocnemius.

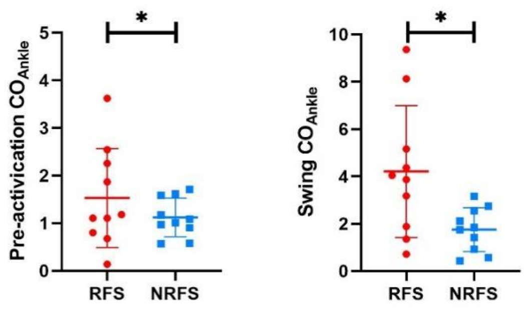

Figure 1: Effects of habitual running foot strike pattern on the pre-activation CO_{Ankle} (the left column) and swing CO_{Ankle} (the right column).
Note: *Indicates $p < 0.05$
RFS: rearfoot strike pattern; NRFS: non-rearfoot strike pattern; CO: co-activation.

DISCUSSION: This study aimed to determine changes in muscle activation between two habitual foot strike patterns. The results are consistent with hypothesis (3), and inconsistent with hypotheses (1) and (2).
The findings of this study revealed that RFS runners demonstrated a higher level of CO_{Ankle} than NRFS runners during the pre-activation and swing phases. Because co-activation is the

ratio of antagonist muscle to agonist muscle activation, this is similar to previous studies (Ahn, Brayton, Bhatia, & Martin, 2014). Greater co-activation increased ankle apparent stiffness (Latash, 2018), this implies that greater co-activation in RFS runners during the swing phase and pre-activation may be related to ankle stiffness (Xu et al., 2021). Besides, these two foot strike patterns have different GRF patterns (Boyer et al., 2014), so the greater muscle co-activation of RFS runners may be a strategy in response to great impact force during the early of stance.

Latash (2018) suggested, agonist-antagonist co-activation is unreasonable within many optimization approaches to motor control, because muscle co-activation may lead to state redundancy and trajectory redundancy during local motion. Typically, ankle dorsiflexion is used during the swing phase to achieve foot clearance and to control foot strike pattern for the next initial contact (Kadaba et al., 1989), and a high level of ankle co-activation will consume more energy, which does not contribute to the task during the swing phase (Latash, 2018). In the future, the relationship between optimization approaches and foot strike patterns needs to be explored further.

In this study, no differences were found in the RMS of TA, MG, LG, and SOL between habitual RFS and NRFS. Kyröläinen (2005) found that muscle activation increased when running speed increased. Therefore, we presumed that the relatively slow speeds we used in this study led to no differences in RMS between these two foot strike patterns.

Limitations of this study include: (1) statistical parameter mapping analyses were not used; (2) the subjects were all male; and (3) the speed chosen was only 9 km/h.

CONCLUSION: In this study, we examined the difference in muscle activation between habitual RFS and NRFS runners during running. Compared to RFS runners, the co-activation of ankle flexors and extensors in the pre-activation and during the swing period of habitual NRFS runners were lower. This suggested that RFS runners with higher CO_{Ankle} at pre-activation might be a strategy in response to great impact during the early of stance.

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