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Changes in muscle activation patterns when running step rate is increased

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ABSTRACT

Running with a step rate 5–10% greater than one's preferred can substantially reduce lower extremity joint moments and powers, and has been suggested as a possible strategy to aid in running injury management. The purpose of this study was to examine how neuromuscular activity changes with an increase in step rate during running. Forty-five injury-free, recreational runners participated in this study. Three-dimensional motion, ground reaction forces, and electromyography (EMG) of 8 muscles (rectus femoris, vastus lateralis, medial gastrocnemius, tibialis anterior, medial and lateral hamstrings, and gluteus medius and maximus) were recorded as each subject ran at their preferred speed for three different step rate conditions: preferred, +5% and +10% of preferred. Outcome measures included mean normalized EMG activity for each muscle at specific periods during the gait cycle. Muscle activities were found to predominantly increase during late swing, with no significant change in activities during the loading response. This increased muscle activity in anticipation of foot-ground contact likely alters the landing posture of the limb and the subsequent negative work performed by the joints during stance phase. Further, the increased activity observed in the gluteus maximus and medius suggests running with a greater step rate may have therapeutic benefits to those with anterior knee pain.

1. Introduction

Over half of all running related injuries occur at the knee with anterior knee pain being the most common injury [1,2]. While several injury risk factors have been suggested [3,4], abnormal motion and excessive mechanical loading to the knee joint have been suggested as potential contributing factors [5,6]. Changes to one's running form, specifically running with an increased step rate or decreased stride length, has been shown to alter motion and reduce the joint kinetics during stance phase, and therefore proposed as a potential strategy to reduce the risk of tibial stress fracture and anterior knee pain [7–10].

Decreased mechanical energy absorption by the lower extremity joints when running with a 5–10% increase in step rate from one's preferred is associated with changes in lower limb posture at initial foot-ground contact: The knee is more flexed, the foot inclination relative to the ground is reduced and the heel is more underneath the body's center of mass (COM). In addition, running with a greater step rate reduces the biomechanical demands incurred by the hip, reflected in reduced abduction and internal rotation moments [7]. Further, leg stiffness has been found to increase with step rate [11]. While it is clear that changing step rate can affect lower extremity posturing and joint kinetics, the associated changes in neuromuscular activity have not been described. Considering that muscle weakness and timing have also been associated with running-related injury [12–14], understanding how increasing step rate influences neuromuscular activity of the lower limb could have potential implications for injury rehabilitation and prevention.

When both step rate and running speed are increased, greater activity of primary lower extremity muscles (rectus femoris, vastus lateralis, hamstrings, gastrocnemius) is observed throughout the gait cycle (GC), most clearly at initial contact and push-off [15]. However, it is unlikely that this same response would occur if step rate alone was increased. Given the reduction in knee and hip joint moments during loading response with increased step rate, a corresponding decrease in muscle activity may occur.

The purpose of this study was to characterize the changes in neuromuscular activity during running when step rate was increased while speed was held constant. Based on the known changes in joint kinematics and kinetics [7], we hypothesized that running at a step rate greater than one's preferred would result in decreased muscle activities during the loading response and increased activities during late swing phase. Additional regions of the GC specific to the muscles known period of activation were also considered.

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2. Methods

2.1. Subjects

Forty-five healthy adult volunteers (20 females, 25 males; age, 32.7 ± 15.5 yrs; height, 176.3 ± 10.3 cm; mass, 69.5 ± 13.1 kg) familiar with treadmill running agreed to participate in this study. All subjects ran a minimum of 24.1 km/wk (15 miles/wk; average volume, 29.8 ± 15.5 miles/wk) and had been running for at least 3 months prior to study enrollment. Subjects were excluded if they experienced a leg injury in the prior 3 months; had undergone hip, knee, or ankle joint surgery; or currently had pain in their back or lower extremities while running. The testing protocol was approved by the Health Sciences Institutional Review Board at the University of Wisconsin-Madison, and subjects provided written informed consent in accordance with institutional policies.

2.2. Experimental protocol

Before data collection, each subject's preferred speed (2.9 ± 0.5 m/s) and step rate (172.6 ± 8.8 steps/min) were determined while running on a treadmill for 5 min. Subjects were asked to run at their preferred speed under three step rate conditions: preferred, +5% and +10% of preferred. The order of step rate conditions was randomized for each subject, with a digital audio metronome used to facilitate the appropriate step rate. Data were recorded for 15 s of each condition and did not begin until the subjects were able to maintain the prescribed step rate for a minimum of 1 min determined by visual inspection.

2.3. Data acquisition

Whole body kinematics were recorded (200 Hz) during all running conditions using an 8-camera passive marker system (Motion Analysis Corporation, Santa Rosa, CA, USA), which tracked 40 reflective markers placed on each subject, with 21 located on anatomical landmarks. An upright calibration trial was performed to establish joint centers, body segment coordinate systems, segment lengths and the local positions of tracking markers. A voluntary hip circumduction movement was also performed, with the corresponding kinematic data used to estimate the functional hip joint center in the pelvis reference frame [16]. Kinematic data were low-pass filtered using a bidirectional, 4th order Butterworth filter with a cutoff frequency of 12 Hz. Three dimensional ground reaction forces and moments were simultaneously recorded at 2000 Hz using an instrumented treadmill (Bertec Corporation, Columbus, OH). These ground reactions were then low-pass filtered using a bidirectional, 6th order Butterworth filter with a cutoff frequency of 100 Hz. Foot contact and toe-off times were identified when the vertical ground reaction force exceeded or fell below 50 N, respectively, and were used to determine the stance and swing portions of the GC. Five successive strides of the right limb for each subject were analyzed during each step rate condition. The joint kinematic and kinetic results from this study have been previously reported [7]. The goal of this paper is to expand on the kinematic and kinetic analyses by investigating how the neuromuscular activation may be altered when step rate is increased.

Electromyography (EMG) was simultaneously recorded with the kinematics and kinetics at 2000 Hz using wireless (28 subjects; Trigno™ Wireless System, DelSys, Inc, Boston, MA, USA) or wired (17 subjects; DE-2.1 electrodes and Bagnoli™ DelSys, Boston, MA, USA) surface EMG electrodes placed on the gluteus medius, gluteus maximus, rectus femoris, vastus lateralis, medial and lateral hamstrings, medial gastrocnemius and tibialis anterior muscles of the right lower limb [17]. Each electrode pre-amplified the signal and was interfaced to an amplifier unit (Delsys, Inc, Boston, MA, USA, operating range 40 m, transmission frequency 2.4 GHz, CMRR > 80 dB; bandwidth of 450 Hz at >80 dB/s). The EMG signals were subsequently full-wave rectified and low pass filtered using a bidirectional, 6th order Butterworth filter with a cutoff frequency of 50 Hz.

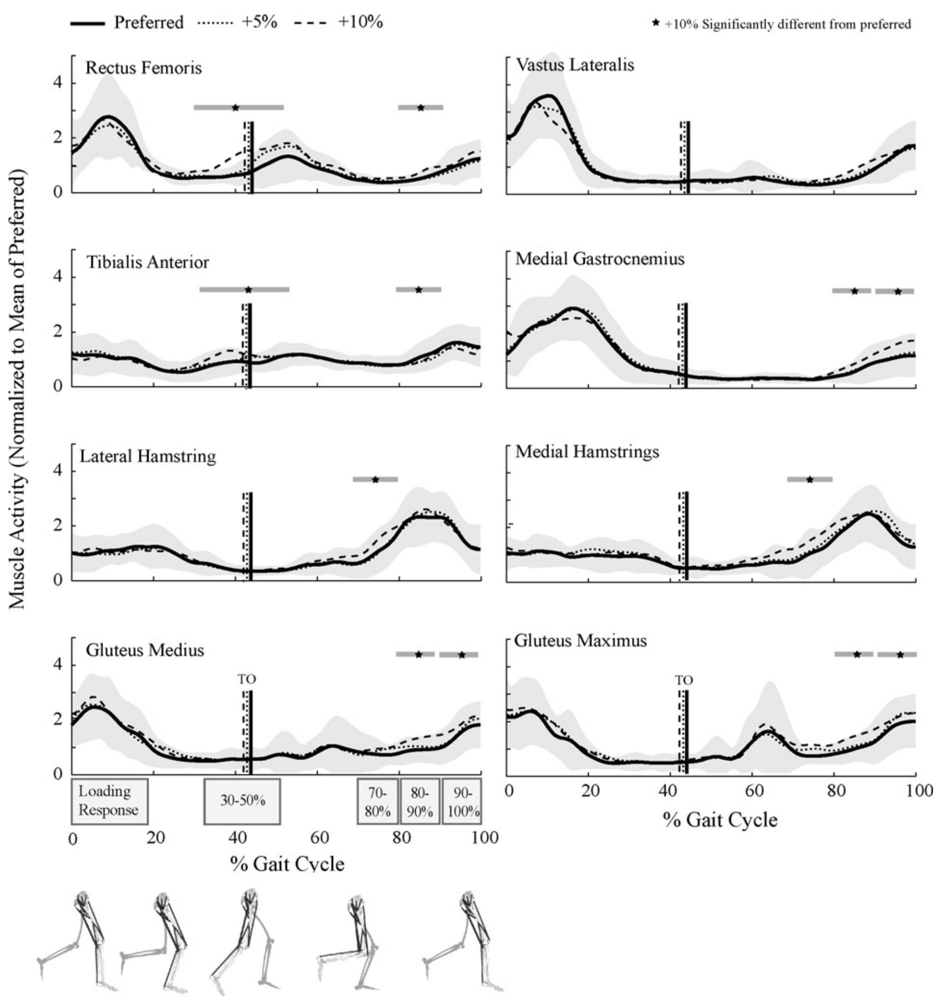

Fig. 1. When running at a step rate 10% above preferred, average muscle activities significantly increased (starred gray horizontal lines) during mid to late swing phase for all muscles except tibialis anterior (decrease) and vastus lateralis (no change). Mean muscle activities did not change during loading response for any of the muscles, with rectus femoris and tibialis anterior displaying increased activity during pre- and initial swing. The gray shaded region is the mean ± SD of preferred step rate, with the vertical line indicating toe off (TO). Gait cycle regions of interest are highlighted at the bottom of the first column.

2.4. Musculoskeletal model

The modeling procedures have been previously described in detail [7]. In brief, the body was modeled as a 14-segment, 31 degree of freedom (DOF) articulated linkage, with the anthropometric properties of body segments scaled to each individual using the subject's height, mass, and segment lengths [18]. For each stride, joint angles were computed at each time step using a global optimization routine to minimize the weighted sum of squared differences between the measured and model marker positions [19].

2.5. Outcome measures

Mean EMG activity for each muscle was determined during specific phases of the running GC: (1) loading response, defined as foot contact (0% GC) to peak knee flexion angle (~15% GC), when significant changes in joint kinematics and kinetics have been observed [7]; (2) late swing/pre-activation (80–90% and 90–100% GC) for all muscles corresponding to approximately 50 and 100 ms prior to foot contact [15,20,21]; (3) pre-swing/early swing (30–50% GC) for tibialis anterior and rectus femoris, capturing the region when these muscles are active [22]; (4) mid-late swing (70–80% GC) for the hamstrings, when these muscles are thought to be most active [22]. Mean EMG activity for each period was then normalized to the average of the respective muscle activity across the entire GC of that subject's preferred step rate condition.

2.6. Statistics

The potential effect of using two different EMG electrodes was investigated using correlation analysis and independent t-tests. Muscle activity variables were compared across step rate conditions for each outcome measure using a 1-factor ANOVA with repeated measures (STATISTICA 6.0, StatSoft, Inc, Tulsa, OK, USA). Post hoc analyses of significant main effects were further investigated using Tukey's HSD, specifically those involving comparison to the preferred step rate condition. Significance for all variables was established at $p < 0.05$.

3. Results

No bias was introduced by the use of two different EMG electrodes (wireless and wired). Significant correlations between electrodes were found for the mean EMG values of each muscle ($r = 0.77–0.98$ $p < 0.0001$), with no effect of electrode type on the individual outcome variables.

The average EMG curves for each muscle during each step rate condition are displayed in Fig. 1, while Table 1 summarizes the EMG values by muscle for each region of the GC. No differences were observed between the preferred and +5% step rate condition. Significant changes between the preferred and +10% step rate conditions during each region of the GC are as follows:

Loading response (0~15% GC). No effect of step rate was observed for any of the muscles ($p = 0.14–0.97$).

Pre-swing/early swing (30–50% GC). Rectus femoris and tibialis anterior activity increased ($p < 0.001$).

Mid-late swing (70–80% GC). Lateral ($p < 0.05$) and medial ($p < 0.01$) hamstring activities increased.

Late swing/pre-activation (80–90% GC). Gluteus maximus and medius, rectus femoris and medial gastrocnemius activities increased ($p < 0.01$), while the tibialis anterior activity decreased ($p < 0.01$). Vastus lateralis activity appeared to increase but was not statistically different ($p = 0.057$).

Late swing/pre-activation (90–100% GC). Gluteus maximus and medius, and medial gastrocnemius activities increased ($p < 0.05$).

4. Discussion

We measured the lower extremity EMG patterns of healthy adults during running at various step rates while speed was held constant. As anticipated, our results showed a predominant increase in activity during late swing phase when step rate was increased, suggestive of an anticipatory pre-activation for the impending foot-ground contact. Contrary to our hypothesis, however, muscle activities during the loading response were not reduced as step rate increased.

Muscle activity during late swing, or pre-activation (80–90 and 90–100% GC), has been suggested to play an important preparatory role for foot-ground contact [23]. Specifically, pre-activation enhances the muscle activity during the subsequent loading

Table 1
Mean ± SD of muscle activity at specific periods during the gait cycle (GC). Muscle activity was normalized for each muscle to the average over the entire stride of each subject's preferred step rate.

Muscle	Step rate	Stance		Swing		
		Loading response	30–50% GC	70–80% GC	80–90% GC	90–100% GC
Vastus lateralis	Preferred	3.0 ± 0.9			0.5 ± 0.4	1.4 ± 0.8
	+5%	2.8 ± 1.3			0.7 ± 0.5	1.3 ± 0.9
	+10%	2.8 ± 1.4			0.8 ± 0.9	1.3 ± 1.0
Rectus femoris	Preferred	2.3 ± 1.0	0.5 ± 0.3		1.0 ± 0.7	0.7 ± 0.4
	+5%	2.2 ± 1.1	0.5 ± 0.3		1.0 ± 0.6	0.9 ± 0.6
	+10%	2.3 ± 1.3	0.7 ± 0.6*		1.2 ± 1.0*	1.3 ± 1.0
Tibialis anterior	Preferred	1.0 ± 0.5	0.8 ± 0.5		1.5 ± 0.6	0.8 ± 0.3
	+5%	1.2 ± 0.7	0.9 ± 0.5		1.3 ± 0.6	0.9 ± 0.4
	+10%	1.0 ± 0.6	1.1 ± 0.5*		1.3 ± 0.6*	1.1 ± 0.5
Medial gastrocnemius	Preferred	2.0 ± 0.8			0.5 ± 0.5	1.0 ± 0.7
	+5%	2.0 ± 1.0			0.6 ± 0.4	1.0 ± 0.7
	+10%	2.0 ± 0.9			0.8 ± 0.8*	1.5 ± 1.6*
Lateral hamstring	Preferred	1.0 ± 0.5		1.1 ± 0.8	2.2 ± 1.0	1.6 ± 1.1
	+5%	1.0 ± 0.7		1.0 ± 0.8	2.3 ± 1.0	1.7 ± 0.8
	+10%	1.1 ± 0.8		1.3 ± 0.7*	2.4 ± 1.4	1.6 ± 0.8
Medial hamstrings	Preferred	0.9 ± 0.5		1.0 ± 0.8	2.2 ± 1.0	1.7 ± 0.9
	+5%	1.0 ± 0.4		1.1 ± 0.8	2.1 ± 1.3	1.9 ± 1.1
	+10%	1.0 ± 0.5		1.3 ± 0.7*	2.3 ± 1.5	1.8 ± 1.0
Gluteus maximus	Preferred	1.9 ± 1.0			0.9 ± 0.6	1.7 ± 1.0
	+5%	2.0 ± 0.8			1.0 ± 0.7	1.9 ± 1.3
	+10%	2.4 ± 1.9			1.4 ± 1.0*	2.1 ± 1.3*
Gluteus medius	Preferred	2.1 ± 0.9			0.8 ± 0.6	1.4 ± 0.7
	+5%	2.2 ± 1.1			1.0 ± 0.6	1.5 ± 0.9
	+10%	2.4 ± 1.1			1.3 ± 0.8*	1.8 ± 1.0*

*Indicates significant differences from preferred step rate ($p < 0.05$).

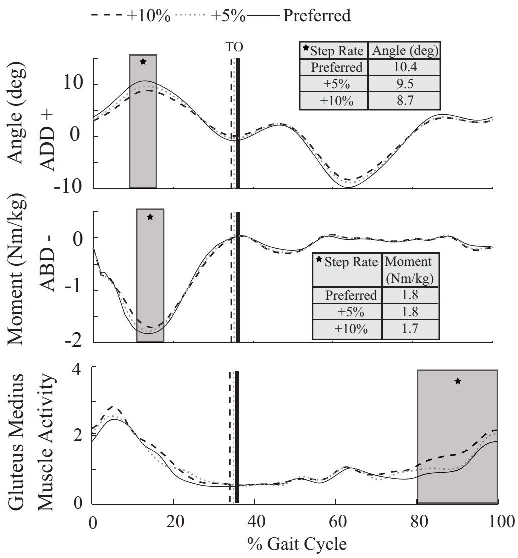

Fig. 2. Gluteus medius activity increased during terminal swing when preferred step rate was increased by 10%. This pre-activation evident in the primary hip abductor muscle may enable the reduction of peak hip adduction angle and peak hip abduction moment evident during the subsequent stance phase.
Data from [7]. * Indicates significantly different from preferred step rate ($p < 0.05$).

response phase, thereby influencing and regulating leg stiffness [24]. In particular, reduced hamstring pre-activity has been suggested as a primary factor in reduced running economy, resulting from the associated increase in the braking impulse upon landing [23]. Thus, the increased hamstring activity during mid swing (70–80% GC) observed when running at a higher step rate likely plays an important role in facilitating the change in landing posture, and reduced knee joint moments and energy absorption we previously observed [7]. Similarly, the increased pre-activation of the gastrocnemius and decreased tibialis anterior activity is likely associated with the reduced foot-ground inclination angle present at initial contact when running step rate is increased [7].

Running with an increased step rate has been shown to decrease peak hip adduction angle and decrease hip abduction moment during the stance phase (Fig. 2) [7]. It is plausible that the increased activities observed for the gluteus medius and maximus during late swing phase influenced this change in frontal plane hip kinematics and kinetics during stance phase. While non-injured runners were investigated for this study, these results suggest that running with an increased step rate may be of benefit to those with anterior knee pain. For example, current rehabilitation programs [12,25] frequently target the gluteus maximus and medius secondary to observed weakness in these muscles [13,14,26] and altered kinematics at the pelvis, hip, and knee [27]. Thus, running at an increased step rate may serve as a therapeutic exercise by facilitating the activation of the gluteus maximus and medius muscles.

Considering the increased inertial contribution of each lower extremity segment during swing phase [28] when step rate is increased (i.e. greater angular velocities at higher step rates), it is not surprising that an increase in muscle activity during mid to late swing (70–80% GC, 80–90% GC, and 90–100% GC) was observed in most of the muscles. While similar changes in muscle activation were evident when step rate was increased by 30% [28], our findings indicate that even a 10% increase in step rate results in greater muscle activity during swing phase. In addition, increased activity of the rectus femoris and tibialis anterior when running at a higher step rate was evident during pre-swing and initial swing (30–50% GC). Because of the decreased time spent in stance and swing phase when running step rate is increased but speed is held constant, the greater activity at pre-swing and initial swing (30–50% GC) is likely needed to achieve greater joint angular velocity in order to maintain a higher step rate. Whether the changes we found in muscle activity are a persistent neuromuscular alteration or simply a temporary adjustment to attaining a higher step rate remains uncertain. Further research is needed to ascertain if these changes are still evident in runners who self select a higher step rate or if these changes will persist after a runner has trained at the higher step rate for an extended period of time. In addition to the observed neuromuscular changes that occur with an increased step rate, there may be an associated metabolic consequence. However, previous research suggests that increasing an individual's step rate by 10% above preferred does not significantly increase oxygen consumption [9].

The results from this study show that increasing step rate is associated with an increase in muscle activity primarily during late swing phase. This increased muscle activity in anticipation of foot-ground contact likely alters the landing posture of the limb and subsequent joint moments and energy absorption. Further, the increased activity observed in the gluteus maximus and medius suggests running with a greater step rate may have therapeutic benefits to those with anterior knee pain.

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Conflict of interest statement

There is no conflict of interest.

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