5-2012

Muscular Activity Characteristics Associated With Preparation for Gait Transition

Li Li
Georgia Southern University, lili@georgiasouthern.edu

Lorna L. Ogden
Louisiana State University

Available online at www.sciencedirect.com

SciVerse ScienceDirect

Journal of Sport and Health Science 1 (2012) 27–35

www.jshs.org.cn

Original article

Muscular activity characteristics associated with preparation for gait transition

Li Li*, Lorna L. Ogden

Department of Kinesiology, Louisiana State University, Baton Rouge, LA 70803, USA

Received 27 October 2011; revised 30 November 2011; accepted 8 December 2011

Abstract

Purpose: The purpose of this study was to investigate lower extremity neuromuscular activity patterns during gait transitions with continuously changing locomotion speeds.

Methods: Muscular activities related to gait transitions (walk to run and run to walk) induced by changing treadmill speed were compared to muscular activities during walk and run at constant speeds. All transition and constant speed conditions were conducted in similar speed range. Surface electromyographic activities of gluteus maximus (GM), rectus femoris (RF), vastus lateralis (VL), biceps femoris long head (BFL), tibialis anterior (TA), gastrocnemius (GA), and soleus (SL) were collected and analyzed. The influences of speed and mode of locomotion were analyzed.

Results: We have observed transition specific nonlinear muscular behavior in this study. For example, peak magnitudes of GM, RF, GA, and SL increased with speed quadratically as locomotion approached walk to run transition within the last five steps. Activity duration of GA decreased in a quadratic fashion with speed as approached run to walk transition within the last five steps. These nonlinear reactions to speed change were only observed in transition related conditions but not in the constant speed conditions.

Conclusion: These results indicated that, in preparation for transition, neuromuscular modifications occur steps before gait transition due to changing speed. Gait transition is not a spontaneous event in response to any type of triggers.

Keywords: Biomechanics; Electromyography; Locomotion; Neuromuscular control

1. Introduction

It is known from animal studies that neuromotor patterns change in respect to gait patterns.[1,2] Through the use of surface electromyography (EMG), these changes were also investigated in humans. Based on their earlier study, Hreljac et al.[3] have tested the hypothesis that gait pattern was changed from walk to run in order to reduce muscular stress on the dorsiflexor while simultaneously placing more demand on the larger muscles of the lower extremity. EMG activity of the tibialis anterior (TA), medial gastrocnemius (GA), vastus lateralis (VL), biceps femoris long head (BFL), and gluteus maximus (GM) have been monitored while participants walked at constant speeds of 70%, 80%, 90%, and 100% of their preferred walk to run (WR) transition speed and ran at their preferred WR transition speed. Results have shown that the peak normalized EMG activity for TA increased as walking speed increased, then decreased when gait changed to a run at preferred transition speed. The peak normalized EMG activities of the VL, GA, and BFL all have increased as walking speed increased, then have increased further when gait changed from walk to a run at the preferred WR transition

* Corresponding author.
E-mail address: LLI3@lsu.edu (L. Li)
Peer review under responsibility of *Shanghai University of Sport*

Production and hosting by Elsevier

doi:10.1016/j.jshs.2012.04.006

speed. The researchers[3] have suggested that humans change gait patterns to prevent overexertion and possible injury to the relatively small dorsiflexor muscles which were working close to maximum capacity when walking at or above the preferred WR transition speed.

To further investigate muscle behavior in gait transitions, muscle functions have been observed in stance and swing phase separately. Prilutsky and Gregor[4] reported that during both walking and running at all studied constant speeds, the soleus (SL), GA, VL, and GM have their activity bursts primarily during the stance phase, and TA, rectus femoris (RF), and BFL were the major muscles controlling the swing phase. Observation has shown that the activation of muscles with swing-related function (TA, BFL, and RF) is typically lower during running than during walking at preferred running speeds (115%, 130%, and 145% of the preferred WR transition speed), and the average EMG activity of muscles with pure support-related functions (SL, GA, VL, and GM) is typically lower during walking than during running at preferred walking speeds (55%, 70%, and 85% of the preferred WR transition speed). Prilutsky and Gregor[4] suggested that exaggerated swing-related activation of the TA, RF, and BFL is primarily responsible for the WR transition at increased walking speed and higher support-related activation of the SL, GA, and VL triggers the run to walk (RW) transition at decreasing speed.

The abovementioned reports[3,4] described muscle activity at constant locomotion speed ranges close to preferred gait transition speed and suggested that the gait transitions were an instantaneous event in response to some types of trigger. Other researchers[5–7] suggested a dynamical systems approach to better describe locomotion mechanisms and predict the various parameters related to gait transition. In applying such an approach, locomotion is treated as a self-organizing system. Walking and running are distinguished as different attractor states. Gait transitions represent the bifurcations the attractor states experience when velocity is changed as a control parameter. Nonlinear behavior is often observed as systems approach bifurcation, and system behavior changes gradually as it approaches the bifurcation. Recent support to the nonlinear behavior of gait transitions has shown a quadratic trend of vertical ground reaction forces in relation to locomotion speed as approaching toward gait transition.[8,9]

Gait transition related EMG studies[3,4] only provide possible explanations of muscle activity during stable speeds. They do not mention muscular activity changes as locomotion speeds approach the preferred transition speed as shown with other gait parameters.[5,8,9] Li and Hamill,[9] as well as Nimbarte and Li[10] have presented evidence concerning speed change effects on the behavior of kinetic gait parameters. Instead of observing the gait parameters (vertical ground reaction force, VGRF) at a range of constant speeds including the transition speeds, observations were made as the participants' locomotion speed continuously changed via (+/−) constant acceleration, while approaching preferred gait transition speed. Nonlinear trends for VGRF were observed within five steps before WR transition with out-of-proportion greater changes observed during the last steps before transition. The behavior of VGRF immediately before gait transition with continuous changed speed was different from behavior associated with constant speed in the same speed range. This change cannot be explained by the existence of acceleration since acceleration was constant across all the trials. Their results were supported by dynamical system-based predictions.[5,8] Therefore, muscular patterns at speeds near transition (before and after) should also vary non-linearly as other mechanical parameters observed.[5,8–10] However, the previous transition related studies[3,4,11] could not provide detailed information regarding how the lower extremity muscle activity pattern changes as approaching gait transitions with continuous velocity change, since their experiments were all performed at different constant velocities.

Therefore, the purpose of this study was to further investigate the differences of muscular activity patterns during gait transitions approached by continuously changing speeds. We hypothesize that nonlinear muscular activity is associated with gait transitions when approached by changing locomotion speed whereas muscle activity changes linearly with the increase of stable locomotion speeds in the vicinity of gait transition speed.

2. Methodology

2.1. Participants

Twelve volunteers (9 males and 3 females) recruited from the community of Louisiana State University with age (mean $\pm$ SD): 21 $\pm$ 2 years old; mass: 78 $\pm$ 18 kg; and stature: 1.8 $\pm$ 0.1 m. Informed consent was obtained from all subjects prior to data collection according to the Institutional Review Board approval; any exclusion was based on pre-existing gait dysfunctions.

2.2. Equipment

To identify gait cycle and speed at which gait transition occurred a motorized treadmill with imbedded force platforms (Kistler Gaitway™; Kistler Instrument Corporation, Amherst, NY, USA) was used in the experiment. EMG data were collected using a 16-channel surface EMG system (MA-300-16 EMG System©, Motion Lab Systems Inc., Baton Rouge, LA, USA). The EMG system specifications consisted of: $\pm$5 V full scale EMG signal output level with gain suitable for each channel, 3−2000 Hz at −3 dB standard EMG bandwidth, electric isolation capability of 600 V DC, and 60 feet RG-174 cable at 3 mm diameter for signal connection to a desktop interface unit. The electrodes consisted of modular, surface-mount pre-amplifiers with full static and muscle stimulation protection and four dry button pre-amplifier contacts. The contacts were approximately 2 cm apart at the center of each button.

2.3. Experiment preparation

The sampling frequency was set at 960 Hz for the force platform embedded treadmill and the EMG. Surface electrodes were placed parallel to the muscle fibers at the respective muscle bellies for GM, RF, BFL, VL, TA, lateral head of GA, and SL. The amplifier gains for each channel were adjusted to appropriate levels. The warm-up session started for walking at 1.3 m/s and then adjusted to running at 2.7 m/s for a total of 5 min. Data collection started within 5 min after warm-up.

2.4. Protocols

Four different conditions were designed among which two different protocols were required to test the conditions. See Fig. 1 for schematic representation of the four different conditions. The first protocol, continuously changing speeds, included WR and RW transition conditions. The second protocol resembled the previous interval speed-based studies.[11] Walking (WC) and running (RC) with constant speeds conditions were designated. Since one of the observations from the WR and RW protocols was required to formulate the speeds tested in the WC and RC protocols, WR and RW were presented first.

There were five trials included in each of the WR and RW protocols. For WR, data collection began after the participant walked on the treadmill for 20 s at 0.9 m/s. While recording, the experimenter continuously accelerated the treadmill provoking a transfer to running. The treadmill acceleration

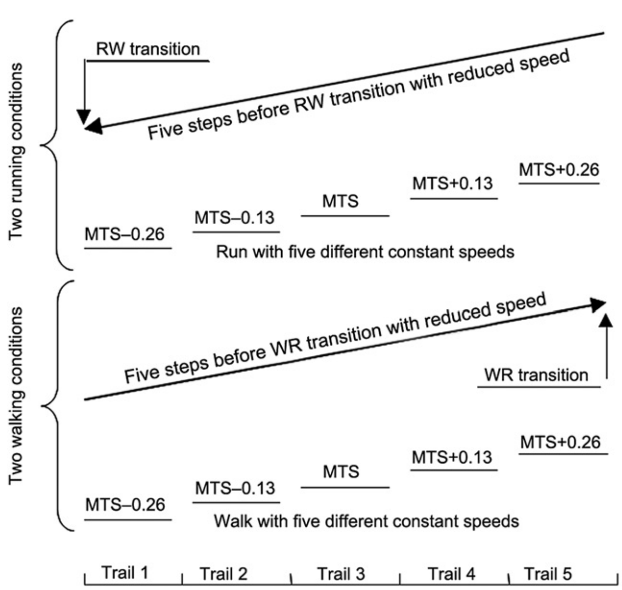

Fig. 1. Schematic representation of the four testing conditions. There were two conditions where treadmill speed changed constantly until gait transitions were induced. Walking with increased speed lead to WR transition (condition 3), and running with decreased speed lead to RW transition (condition 1). Two additional conditions included walking (condition 4) and running (condition 2) at five different constant speeds. Trials 1−5 for conditions 1 and 3 consisted of five steps before gait transition, where trials 1−5 for conditions 2 and 4 referred to the five different constant speed. MTS mean transition speeds; RW means run to walk; WR means walk to run.

was terminated after observing the WR transition. The magnitude of acceleration/deceleration was controlled manually by pressing the acceleration/deceleration button at 1 Hz with the beep of a pre-set metronome, which resulted in a consistent rate of velocity change at 0.14 m/s^2 for both conditions. A qualified collection for both conditions consisted of six observed left heel contacts prior to the transition, which consisted of five consecutive stride cycles. Each of the five consecutive left foot stride cycles was designated as a separate trial. Five qualified collections were taken for both conditions. The testing order of the two types of transitions (WR and RW) was balanced to avoid any order effects.

Gait transition speeds were determined based on vertical ground reaction force collection synchronized with speed collection on the Gateway treadmill. WR transition speeds were determined as the mean speed between the speed of the last point of the last walking stance phase and speed of the first point of first running stance phase. Walking and running stance phase were determined based on how many peaks the vertical ground reaction forces presented. There are two peaks for walking and one for running. RW transition speeds were determined in the same manner with the last running and first walking stance phases. The mean transition speed of each participant was calculated as an average of the five WR and five RW transition speeds before proceeding to the second session.

Constant speed ranges entailed WC (condition 4 in Fig. 1) and RC (condition 2 in Fig. 1) at set speed intervals for five trials. The speed range for each subject depended on the mean of the recorded transition speeds (MTS) for both WR and RW from the preceding session. Interval speeds were determined from MTS as follows: MTS $\pm$ 0.13 m/s, MTS $\pm$ 0.26 m/s, and the MTS value. This selection of speeds insured that the speed ranges of WR, RW, WC and RC were comparable. The selection of speed range is based on our previous observations[9,12] to ensure that the lower and upper limit (MTS $\pm$ 0.26 m/s) was close to RW and WR, respectively. For each speed, ten seconds of data collection followed 20 s of acclimation, then 20 s of rest. The order of the tests was balanced to avoid any potential order effects.

2.5. Data processing

Heel contacts at the initiation of the stance phase and toe off at the initiation of the swing phase were identified with vertical ground reaction force recordings. Stride cycle was defined as consecutive heel contacts for both walking and running trials. Gait transitions were identified by the differentiation between double stance and double flight phase observed in vertical ground reaction forces in walking or running, respectively.

EMG signal bias (mean of the raw EMG data from each muscle) was removed before a full-wave rectification. As a result of the residual analysis,[13] a fourth order, zero lag Butterworth, digital filter was employed to process the data at a cutoff frequency of 6 Hz. The sections of the linear envelope that corresponded with the previously determined stride cycles

for each condition were extracted and scaled to 100% of the stride cycle.

Ensemble curves were calculated across the repeated progressions with its respective stride for all muscles and subjects within the WR and RW conditions. The averaged strides were now considered trials, totaling 5 in number across all muscles and subjects. Trials 1, 2, 3, 4, and 5 represented running steps 1, 2, 3, 4, and 5 before transition in RW condition. Trials 1, 2, 3, 4, and 5 represented walking steps 5, 4, 3, 2, and 1 before transition in WR condition. For WC and RC conditions, the ensemble curves of five strides extracted from each speed represent the trials for each muscle and subject. The ensembled linear envelopes were classified into four different categories of RC, WC, RW and WR.

EMG activity patterns were determined "on" when the EMG ensemble curve went from below to above 10% of the maximum EMG value of each muscle across all the trials in all conditions. They were determined "off" if the magnitude of the ensemble curve went from above to below 10%. The EMG activation durations were identified as the time between the identified on and off points. The relative peak magnitude (PeakM) of all activity periods was calculated and reported as a percentage of the overall PeakM of each muscle across all the trials in all conditions. Please refer to Fig. 2 for more details of the selection of these EMG parameters.

Condition by trial (4 by 5) factorial analysis of variance (ANOVA) with repeated measures was employed to analyze duration and PeakM with an α level of 0.05. Post hoc polynomial trend analyses were also conducted and reported below only when they were significant ($p < 0.05$).

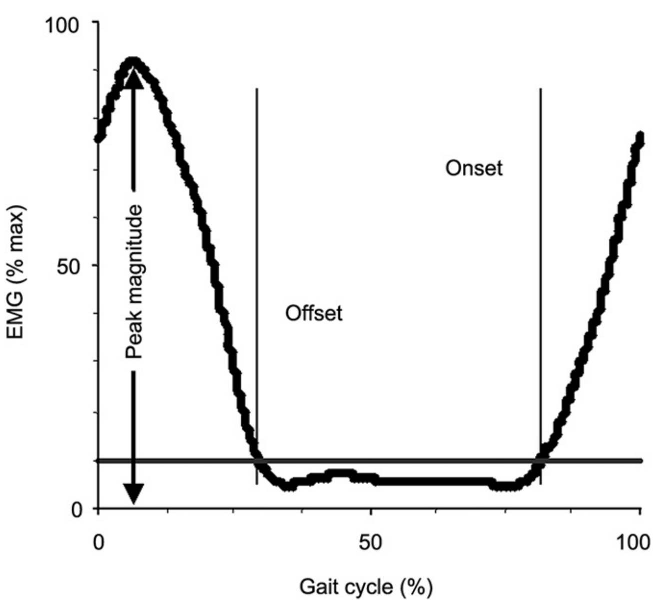

Fig. 2. Exemplar data for the selection of electromyography (EMG) parameters. All calculated EMG parameters were selected from the normalized linear envelop. All temporal events were normalized to 100% gait cycle between two consecutive heel contacts. EMG magnitude of each muscle was normalized to the peak value of that muscle across all the trials of all the conditions. On/offset of EMG activation were determined at 10% normalized values and the duration of activation was estimated by the percentage of gait cycle between the on/offset values.

3. Results

The overall MTS for WR and RW transitions was 2.1 ± 0.5 m/s. This result is similar to data reported in the literature.[7,14]

Fig. 3 displays the EMG activity ensemble curves of all the tested muscles. From these activity patterns, the differences of the overall patterns and most of the discrete parameters can be observed. There were two periods of activation for GM, RF, BFL, and VL muscles within one gait cycle during all four different conditions (Fig. 3). The bottom three panels of Fig. 3 illustrate the ensemble curves of the EMG activity patterns for TA, GA, and SL. TA exhibited two activation peaks (Fig. 3). GA and SL patterns consisted of only one activation peak (Fig. 3).

Dynamical systems theory predicts nonlinear behavior as compared to the trigger mechanisms as locomotion approaches gait transition speed. Evidence supporting the gait transition related nonlinear behavior is presented here as our focus of this section. For example, condition/trial interactions were detected in the PeakM for GM, RF, and VL but not for BFL (Fig. 4). As speed increased, the PeakM of the GM during weight acceptance phase increased for all conditions, but the manner of the increase differed among conditions. The condition and trial (mode and speed) interaction ($F_{12,132} = 2.90$, $p < 0.001$) was demonstrated by several facts: the trend of PeakM for WC ($PeakM_{GM} = 5.6*step + 46.6$, $R^2 = 0.9643$) and RW ($PeakM_{GM} = 3.7*step + 70.9$, $R^2 = 0.7606$) increased linearly as speed increased; no trend of PeakM for RC with speed was detected; the trend of PeakM for WR ($PeakM_{GM} = 1.64*step^2 + 0.24*step + 48.4$, $R^2 = 0.9991$) increased quadratically with greater changes observed upon approaching the gait transition. In addition to the apparent reaction to change of speed as in WC, more changes were observed in WR as transition specific behavior. PeakM of RF during the weight acceptance phase also increased with speed differentially (interaction: $F_{12,132} = 6.83$, $p < 0.0001$). PeakM increased in a linear fashion for WC ($PeakM_{RF} = 6.4*step + 47.4$, $R^2 = 0.8442$) and in a quadratic fashion for WR ($PeakM_{RF} = 2.21*step^2 + 0.41*step + 38.2$, $R^2 = 0.9973$) as the speed effect was amplified by the preparation for gait transition. For the activity patterns of VL when the speed was increased, PeakM for all conditions increased linearly (Fig. 4). However, the magnitude of increase differed between the conditions and RC had no discernable trend resulting in a mode/speed interaction ($F_{12,132} = 6.17$, $p < 0.0001$). The muscles across the ankle joint also demonstrated mode/speed interactions. For example, the activity burst of TA at the heel contact responded to the increase in speed by changing the PeakM differently for different modes (interaction: $F_{12,132} = 5.48$, $p < 0.0001$). The walking conditions PeakM presented an amplitude difference between the activity patterns of WC and WR and a linear increase in magnitude as speed increased for both (Fig. 4). PeakM of GA and SL during stance phases increased across different modes of locomotion as speed increased, while the manner of increase included both linear trends and quadratic trends (interactions: GA:

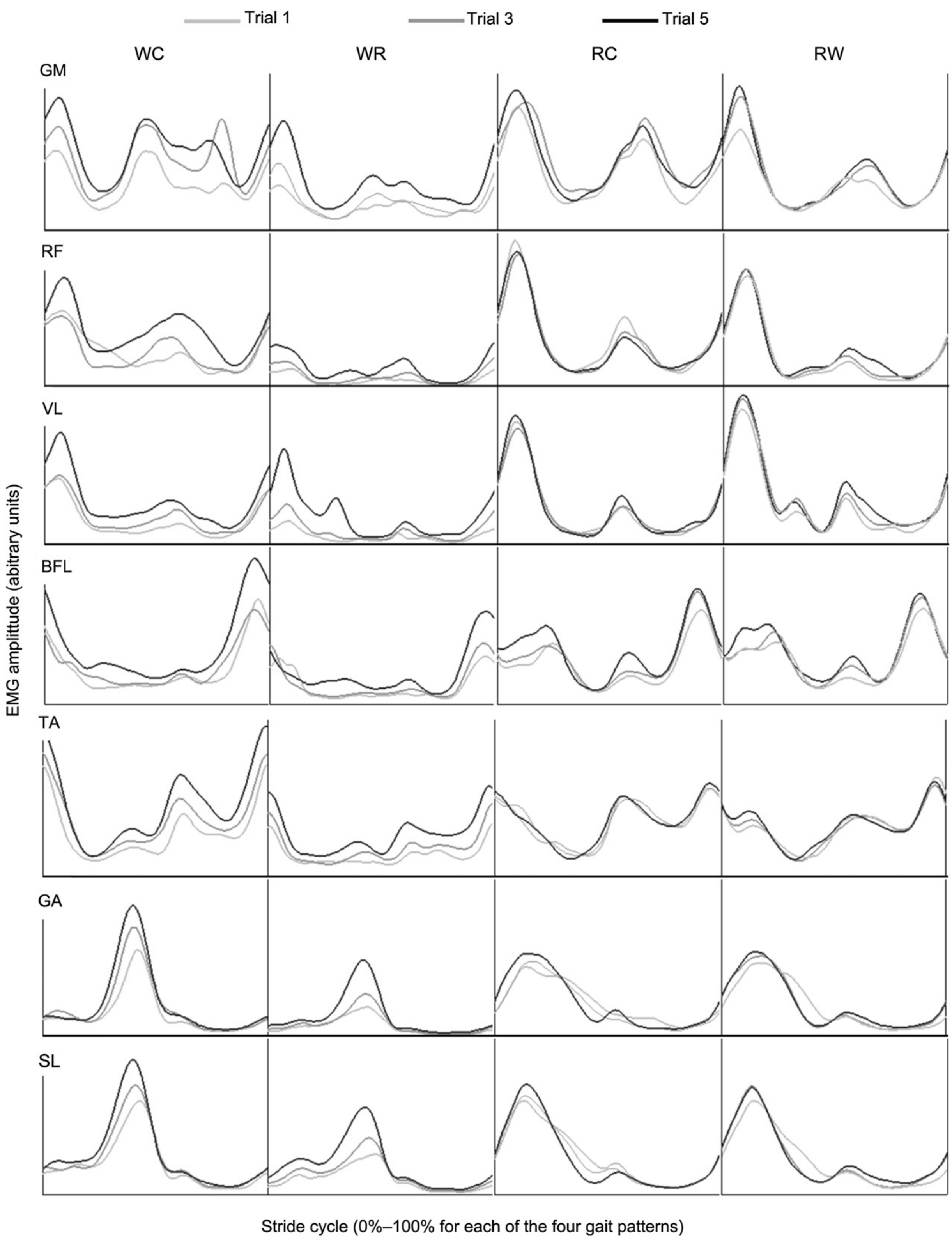

Fig. 3. Muscle activity patterns to illustrate electromyography (EMG) activity changes with both conditions and speed. The ensemble curves of the gluteus maximus (GM), rectus femoris (RF), vastus lateralis (VL), biceps femoris long head (BFL), tibialis anterior (TA), gastrocnemius (GA), and soleus (SL) are represented in the graph. The two walking conditions, walking with constant velocity (WC) and with increased velocity that lead to walk to run transition (WR), comprise the first two columns. Trial 1 represents the furthest step from transition for WR and the slowest walking trial for WC. The trials then progress as either steps nearing transition (WR) or as trials increasing in constant speed (WC) with trial 5 as the fastest trial tested. The remaining two columns are for the running conditions: running with constant velocity (RC) and with decreased velocity that lead to run to walk transition (RW). As in WR, the trials for RW represent the steps nearing transition with trial 1 being the furthest from transition. However speed continuously decreased across the five trials for RW such that trial 1 represents the fastest running trial and the trial furthest from transition. The trial designations for RC are the same as WC such that trial 1 represents the slowest trial, and the trials were increasing with constant speed.

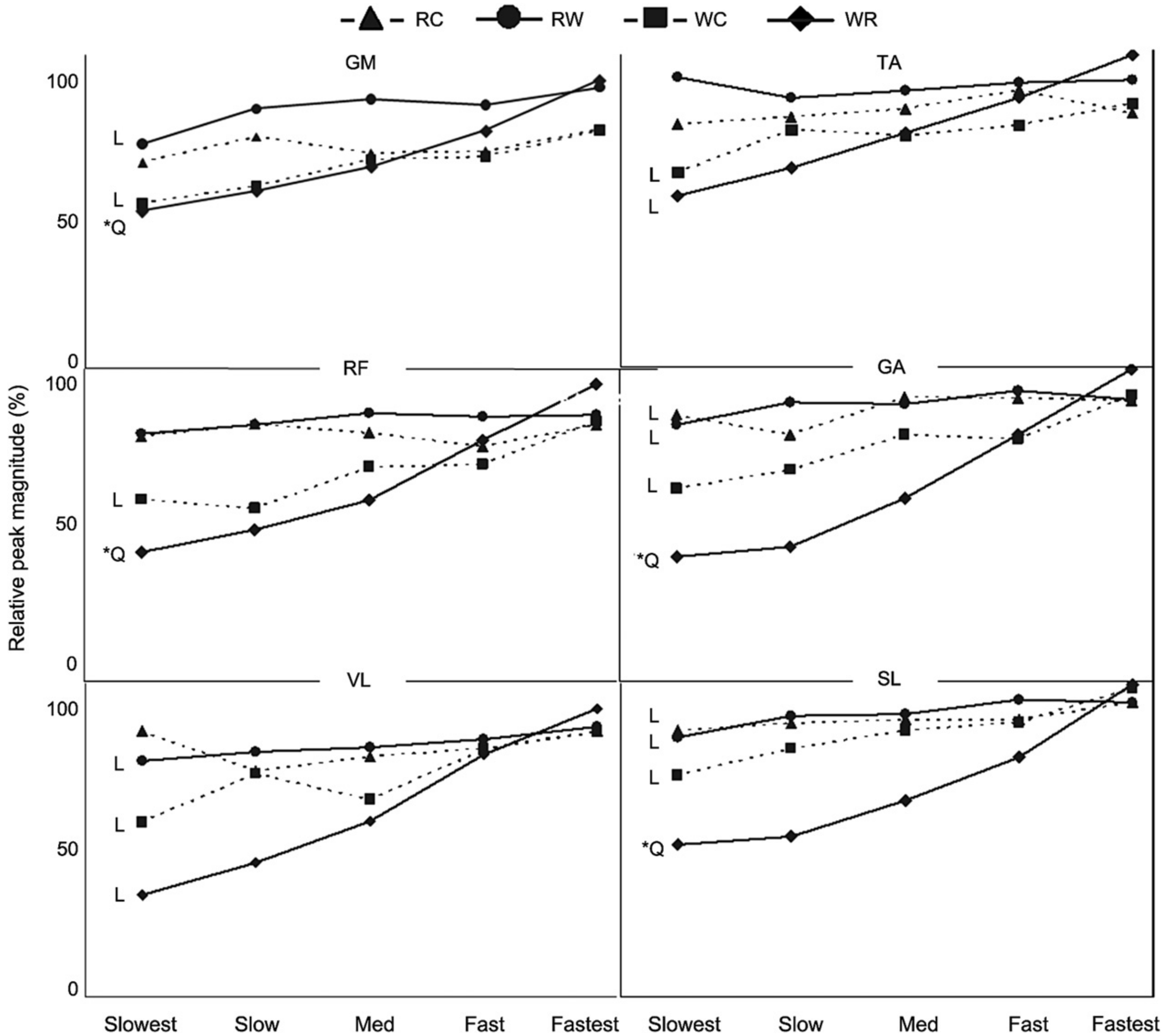

Fig. 4. Peak magnitude for muscle activity patterns. Condition/trial interaction graph for the relative peak magnitude of the first activity period for the muscles of the lower extremity: gluteus maximus (GM), rectus femoris (RF), vastus lateralis (VL), tibialis anterior (TA), gastrocnemius (GA), and soleus (SL). No significant condition/trial interactions were observed for the biceps femoris long head (BFL). The constant velocity conditions for walking and running are WC and RC. WR represents the increasing velocity walking condition leading to a walk to run transition. RW represents the decreasing velocity running condition leading to a run to walk transition. Significant trends, quadratic (Q) or linear (L), were observed for all of the transition conditions with the exception of the RW condition for RF and TA. For the constant velocity conditions, only linear trends were observed if a significant trend was detected.

$F_{12,132} = 16.72$, $p < 0.0001$; SL: $F_{12,132} = 11.55$, $p < 0.0001$). All running conditions (RC: $\text{PeakM}_{GA} = 1.9\text{*step} + 81.1$, $R^2 = 0.3729$; RW: $\text{PeakM}_{GA} = 2.0\text{*step} + 82.4$, $R^2 = 0.6135$) displayed a linear increase along with the constant speed condition of walking (WC: $\text{PeakM}_{GA} = 7.0\text{*step} + 54.0$, $R^2 = 0.9142$); WR exhibited the quadratic trend ($\text{PeakM}_{GA} = 3.07\text{*step}^2 + 2.93\text{*step} + 38.8$, $R^2 = 0.9960$, Fig. 4). The means and standard error of the means of PeakM are presented in Table 1.

Although there were no significant changes in the active duration for GM, VL and BFL observed, RF duration for the two running conditions underwent changes (Fig. 5) as a result of decreased speed in which these changes were not similar across the conditions (interaction: $F_{12,132} = 1.92$, $p < 0.038$). Further analyses revealed that duration increased with speed linearly for WR ($D_{RF} = 2.4\text{*step} + 27.4$, $R^2 = 0.8571$), but decreased linearly for both WC ($D_{RF} = -0.5\text{*step} + 32.5$, $R^2 = 0.4167$) and RW ($D_{RF} = -0.7\text{*step} + 36.5$, $R^2 = 0.5326$) conditions. No significant trends were observed in RC. For TA, the period of the activity burst in the vicinity of the heel contact responded to the increase in speed by changing duration (interaction: $F_{12,132} = 2.58$, $p < 0.004$) of the period differently for the different modes. TA activity duration increased for walking but no change was observed for RC. Activity durations of GA and SL activities changed with the increasing speed across the conditions (GA: $F_{12,132} = 3.27$, $p < 0.0001$; SL: $F_{12,132} = 5.02$, $p < 0.0001$). Each walking activation period of GA remained active longer; this increase in duration was linear in both WC and WR. GA duration decreased in a quadratic fashion with RW ($D_{GA} = 0.64\text{*step}^2 - 4.16\text{*step} + 54.6$, $R^2 = 0.9832$) and exhibited neither trend with RC (Fig. 5). The duration of SL

Table 1
Relative peak magnitude (mean ± SEM) of six selected muscles.

Muscle	Condition	Trail				
		1	2	3	4	5
GA	RC	85 ± 2	79 ± 3	91 ± 2	90 ± 3	89 ± 2
	RW	82 ± 3	89 ± 2	88 ± 2	93 ± 2	90 ± 3
	WC	61 ± 5	67 ± 4	79 ± 5	77 ± 5	91 ± 5
	WR	40 ± 3	43 ± 3	58 ± 3	78 ± 2	100 ± 0
GM	RC	65 ± 6	73 ± 7	68 ± 6	69 ± 6	76 ± 6
	RW	71 ± 4	82 ± 3	85 ± 4	83 ± 4	89 ± 2
	WC	52 ± 7	57 ± 5	66 ± 6	67 ± 7	75 ± 7
	WR	50 ± 3	56 ± 4	64 ± 5	75 ± 6	91 ± 5
RF	RC	78 ± 4	82 ± 2	79 ± 4	75 ± 5	82 ± 3
	RW	79 ± 5	82 ± 5	85 ± 5	84 ± 6	85 ± 5
	WC	58 ± 7	55 ± 7	68 ± 8	69 ± 6	83 ± 8
	WR	41 ± 5	48 ± 4	58 ± 5	77 ± 6	95 ± 3
SL	RC	85 ± 2	87 ± 2	88 ± 3	88 ± 3	93 ± 2
	RW	82 ± 3	89 ± 1	90 ± 2	94 ± 1	94 ± 2
	WC	70 ± 4	79 ± 2	84 ± 3	87 ± 3	98 ± 1
	WR	48 ± 3	51 ± 3	62 ± 2	76 ± 3	99 ± 0
TA	RC	77 ± 4	80 ± 3	82 ± 4	88 ± 3	81 ± 6
	RW	92 ± 3	86 ± 2	88 ± 2	91 ± 2	92 ± 2
	WC	62 ± 6	76 ± 5	74 ± 7	77 ± 7	84 ± 7
	WR	54 ± 4	63 ± 5	74 ± 4	86 ± 4	99 ± 0
VL	RC	84 ± 6	72 ± 7	76 ± 7	79 ± 7	84 ± 7
	RW	75 ± 6	78 ± 6	79 ± 6	82 ± 5	86 ± 5
	WC	55 ± 7	71 ± 7	62 ± 7	78 ± 6	84 ± 8
	WR	32 ± 5	42 ± 5	55 ± 6	77 ± 5	91 ± 4

The peak magnitudes were normalized within subject to the maximum peak value of each muscle across all the trials and conditions. Please see the text for detailed statistical analysis results.
Abbreviations: GA = Gastrocnemius; MA = Gluteus maximus; RF = Rectus femoris; SL = Soleus; TA = Tibialis anterior; VL = Vastus litaritus; RC = running; RW = run to walk; WC = walking; WR = walk to run.

activity linearly decreased as speed increased during both running modes (Table 2).

4. Discussion

The main focus of this study was meant to further quantify and investigate the muscle activity patterns associated with gait transitions, which had previously only been investigated by three studies with constant speeds.[3,4,11] Based on the muscle activity pattern observations of those studies in addition to our previous kinetic observations,[9,10] we hypothesize that nonlinear muscular activity is associated with gait transitions approached by changing locomotion speed where muscle activity changes linearly with the increase of stable locomotion speeds in the vicinity of gait transition speed. The observations of the study support our hypothesis.

The observations of the present study in both the constant speed conditions (RC and WC) produced similar results compared to previous gait transition studies.[3,4,11] Yet, different activity patterns were exhibited in the continuously changing speed conditions (RW and WR) when compared to the constant speed conditions (RC and WC). Therefore, the results supported the presence of activity pattern differences between stable locomotion and transitional locomotion. This observation is supported by our previous data[9] as well as Segers et al.[15] although their data were kinematic in nature. Li and Hamill[9] have reported a nonlinear change of vertical ground reaction forces a few steps before gait (both RW and WR) transitions. Segers et al.[15] reported that the kinematics of the swing phase before WR transition is different from regular walking swing phase and have suggested the change was due to preparation for gait transition.

4.1. Constant velocity and muscle activity between running and walking

Differences between the two gait patterns when conducted at greater or less than preferred transition speeds were evident in all the muscles through overall activity pattern changes. The activation periods of all muscles investigated exhibited changes in magnitude and duration. Activation magnitude increased with increasing speed linearly (if a trend was discernable) for both gait patterns (WC and RC), but the magnitude gains were disproportional such that the magnitude increases for running were less than the increases for walking (GM, RF, VL, TA, GA, and SL). Prilutsky and Gregor[4] and this study observed that activity magnitudes of RF and TA at greater running speeds were less than those at comparable walking. The speed related changes in duration corresponded to a gait related linear increase (RF); the presence and/or disappearance of activation periods (GM, VL, and TA); and the shifting of offset of the periods (GA and SL). Duration of RF activity at the beginning of the stance phase linearly increased in RC while remaining consistent in WC. The longer activation in RC and not in WC was possibly related to the speculated role of providing joint stability along with propelling the body during stance.[16]

4.2. Progressing toward transition versus locomoting at different constant velocities

Although the focus and results of the study of Hreljac et al.[3] and Prilutsky and Gregor[4] were very different, they both speculated that switching from walking to running would reduce the PeakM of the muscular activities of BFL, RF, and TA at greater walking speeds or as the speed advanced beyond the preferred transition speed. Also, switching from running to walking would reduce the PeakM of the muscular activities of GM, VL, GA, and SL during running stance at slower speeds or as the speed reduced to less than the preferred transition speed. However, the actual activity pattern changes during gait transition or preceding gait transition were not included in the generalization nor were they compared to the constant velocity observations. Greater changes in the PeakMs were observed during the WR and RW conditions. PeakM did not change as much with speed change during WC and RC conditions. Furthermore, the manner of change for the magnitudes and durations of the activities had quadratic trends or different linear trends compared to the constant velocities. In general,

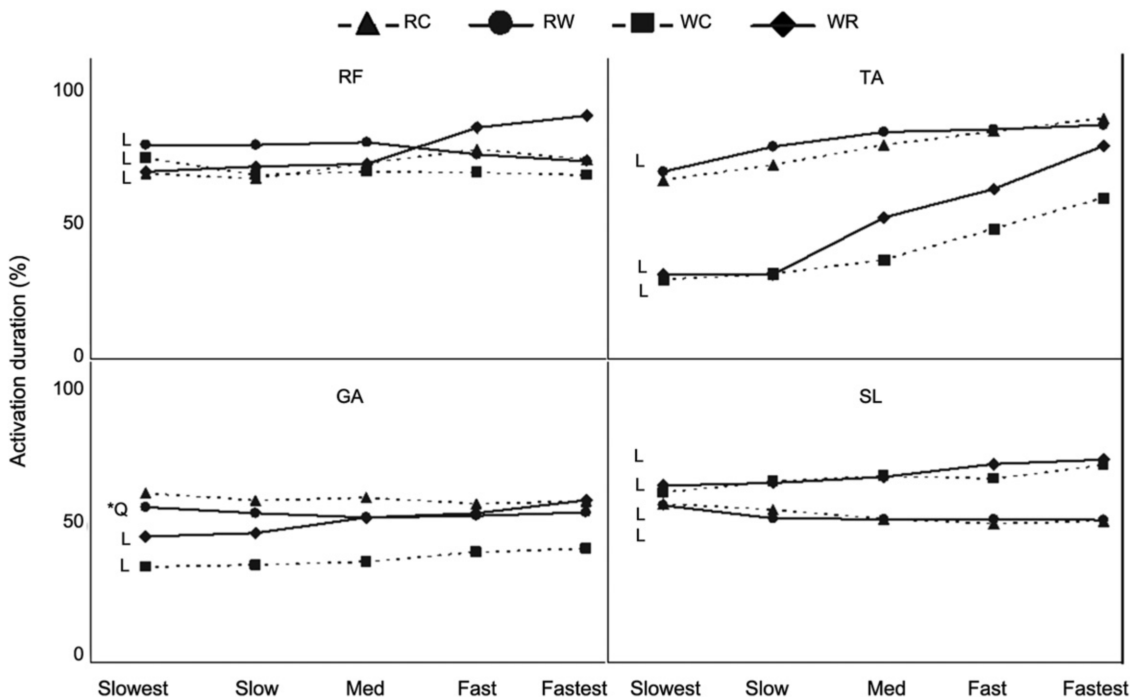

Fig. 5. Activation duration for muscle activity patterns. Condition/trial interaction graph for the duration of the first activity period for the muscles of the lower extremity: rectus femoris (RF), tibialis anterior (TA), gastrocnemius (GA), and soleus (SL). The constant velocity conditions for walking and running are WC and RC. WR represents the increasing velocity walking condition leading to a walk to run transition. RW represents the decreasing velocity running condition leading to a run to walk transition. Significant trends, quadratic (Q) or linear (L), were observed for all of the transition conditions. For the constant velocity conditions, only linear trends were observed.

Table 2
Activation durations (mean ± SEM) of four selected muscles.

Muscle	Condition	Trial				
		1	2	3	4	5
GA	RC	56 ± 5	54 ± 4	54 ± 4	52 ± 4	53 ± 4
	RW	51 ± 4	49 ± 4	48 ± 4	48 ± 4	50 ± 4
	WC	31 ± 4	32 ± 4	33 ± 4	36 ± 4	38 ± 4
	WR	41 ± 5	43 ± 4	48 ± 5	49 ± 5	53 ± 6
RF	RC	30 ± 2	30 ± 1	32 ± 2	34 ± 2	33 ± 2
	RW	35 ± 1	35 ± 1	36 ± 1	34 ± 1	32 ± 1
	WC	33 ± 2	30 ± 3	31 ± 2	31 ± 1	30 ± 1
	WR	31 ± 2	32 ± 2	32 ± 1	38 ± 2	40 ± 2
SL	RC	52 ± 4	50 ± 4	47 ± 3	46 ± 3	47 ± 3
	RW	52 ± 3	48 ± 3	47 ± 4	47 ± 4	47 ± 4
	WC	56 ± 5	60 ± 5	62 ± 5	61 ± 4	65 ± 4
	WR	58 ± 4	59 ± 3	61 ± 4	66 ± 3	67 ± 3
TA	RC	59 ± 6	64 ± 6	71 ± 5	75 ± 5	80 ± 3
	RW	62 ± 7	70 ± 6	75 ± 5	76 ± 5	78 ± 5
	WC	26 ± 2	28 ± 2	32 ± 4	43 ± 5	53 ± 5
	WR	28 ± 4	28 ± 4	47 ± 6	56 ± 6	71 ± 5

The activation duration was defined as the percentage duration where the electromyography (EMG) magnitudes were greater than 10% of the maximum EMG values. Please see the text for detailed statistical analysis results.
Abbreviations: GA = Gastrocnemius; RF = Rectus femoris; SL = Soleus; TA = Tibialis anterior; RC = running; RW = run to walk; WC = walking; WR = walk to run.

those changes were magnified as the steps neared the gait transition. In WR condition, for example, quadratic trends were observed for PeakM of GM and RF during weight acceptance phase, and quadratic trends were also observed for PeakM of SL and GA at later stance. The deviation for a linear reaction to speed increase is evident of the existence of the transition specific behavior. This behavior cannot be explained by the increase of speed since it was only showed in WR but not WC. The existence of acceleration in WR might change the behavior of the muscle activity, but that change would be linear since constant acceleration was applied across all the trials in the WR condition.

Observations based on the ensemble curves and the discrete parameters of the muscles VL and BFL also support the presence of different muscle activity patterns between progression (RW and WR) and gait with constant speeds (RC and WC). The ensemble curves for both VL progressions featured distinct increased activities at approximately 30% of the WR and RW activity patterns, which were not present for the WC and RC activity patterns. The ensemble curves of BFL for the walking conditions displayed a magnitude of activity discrepancy between all trials for WC and WR in which the magnitude for WR was consistently less than WC. The decrease in activity magnitude when running at greater speeds described by Prilutsky and Gregor[4] and observed in the RC condition was not observed in RW. These observations also provided evidence to differentiate transitional behavior from locomoting at constant velocity. For the magnitude and the duration of the muscle activation periods, the changes

observed in the progression conditions were more distinguished from the constant velocity such that: a trend was detected for the progressions but not for the constant velocities (GM, RF, VL, GA); when progressions and constant velocities revealed linear trends, those trends were at different slopes (RF, VL, TA, GA, SL); a quadratic trend was detected for the progressions but not the constant velocities (GM, RF, GA, SL). The activation duration of GA and SL during WR was consistently greater than the activation duration during WC.

Quadratic trends signify a transitional specific behavior that is more distinct as the steps approach the gait transitions. For the WR progression, the last two steps approaching transition possessed the most distinct increases in activation magnitude for the GM, RF, GA, and SL. The GA activation duration for RW initially decreased, but duration remained at the same length as transition neared during the last two steps. Regardless of how the magnitude and duration changed, they exhibited transitional behavior.

5. Conclusion

As previously established with reference to muscle activity patterns, stable and transition locomotion exhibit different muscle activity patterns. Transitional specific muscular activity was observed in this study. More specifically, neuromuscular activity pattern changed steps before the observed gait transition. These results suggest that nonlinear and gait transition specific muscular activity can be observed with changing locomotion velocity. Those activity patterns cannot be observed with constant velocity even in the same range.

References

1. Biewener AA, Gillis GB. Dynamics of muscle function during locomotion: accommodating variable conditions. *J Exp Biol* 1999;**202**(Pt 23):3387−96.
2. Heglund NC, Fedak MA, Taylor CR, Cavagna GA. Energetics and mechanics of terrestrial locomotion. IV. Total mechanical energy changes as a function of speed and body size in birds and mammals. *J Exp Biol* 1982;**97**:57−66.
3. Hreljac A, Arata A, Ferber R, Mercer JA, Row BS. An electromyographical analysis of the role of dorsiflexors on the gait transition during human locomotion. *J Appl Biomech* 2001;**17**:287−96.
4. Prilutsky BI, Gregor RJ. Swing- and support-related muscle actions differentially trigger human walk-run and run-walk transitions. *J Exp Biol* 2001;**204**(Pt. 13):2277−87.
5. Brisswalter J, Mottet D. Energy cost and stride duration variability at preferred transition gait speed between walking and running. *Can J Appl Physiol* 1996;**21**:471−80.
6. Diedrich FJ, Warren WH Jr. Why change gaits? Dynamics of the walk-run transition. *J Exp Psychol Hum Percept Perform* 1995;**21**: 183−202.
7. Li L, van den Bogert EC, Caldwell GE, van Emmerik RE, Hamill J. Coordination patterns of walking and running at similar speed and stride frequency. *Hum Mov Sci* 1999;**18**:67−85.
8. Jordan K, Challis JH, Cusumano JP, Newell KM. Stability and the time-dependent structure of gait variability in walking and running. *Hum Mov Sci* 2009;**28**:113−28.
9. Li L, Hamill J. Characteristics of the vertical ground reaction force component prior to gait transition. *Res Q Exerc Sport* 2002;**73**: 229−37.
10. Nembarte AD, Li L. Effect of added weights on the characteristics of vertical ground reaction force during walk-to-run gait transition. *Hum Mov* 2011;**12**:81−7.
11. Nilsson J, Thorstensson A. Ground reaction forces at different speeds of human walking and running. *Acta Physiol Scand* 1989;**136**:217−27.
12. Li L. Stability Landscape of walking and running near gait transition speed. *J Appl Biomech* 2000;**16**:428−35.
13. Winter DA. *Biomechanics and motor control of human movement*. Toronto: John Wiley & Sons, Inc.; 1990.
14. Hreljac A. Determinants of the gait transition speed during human locomotion: kinematic factors. *J Biomech* 1995;**28**:669−77.
15. Segers V, Lenoir M, Aerts P, De Clercq D. Kinematics of the transition between walking and running when gradually changing speed. *Gait Posture* 2007;**26**:349−61.
16. Besier TF, Lloyd DG, Ackland TR. Muscle activation strategies at the knee during running and cutting maneuvers. *Med Sci Sports Exerc* 2003;**35**:119−27.