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Coordination of the lower extremity muscles during gait transitions

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COORDINATION OF THE LOWER EXTREMITY MUSCLES DURING GAIT TRANSITIONS

A Thesis

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Master of Science

in

The Department of Kinesiology

by

Lorna Louise Ogden
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ABSTRACT

Often the approach to investigating muscular coordination during transitions entailed conducting tests at speeds held constant. This study investigated muscular activity during continuously changing speeds in order to further detail and quantify neuromuscular changes during gait transitions. Twelve healthy adults, 18-41 years of age, were recruited as participants. Informed consent was obtained. Gait transitions were induced by the speed of the treadmill changing with constant acceleration. Reflective markers were placed on anatomical landmarks of the hip, knee, ankle, heel, and 5th metatarsal joint. Bipolar surface electrodes were positioned on the subjects’ skin over the muscular bellies of the gluteus maximus (GM), rectus femoris (RF), vastus lateralis (VL), biceps femoris (BF), tibialis anterior (TA), gastrocnemius (GAS), and soleus (SOL). Electromyographic (EMG) data were collected at 960 Hz. Five transition trials were conducted for both progression modes: walk-to-run (WR) and run-to-walk (RW), and five interval trials were collected for both gaits at constant speeds. Five steps preceding the gait transitions were analyzed. The mean of recorded transition speeds (MTS) was calculated from the prior transition trials. There were five different constant speed trials for walking (WC) and running (RC); the speeds were MTS - 0.6, MTS - 0.3, MTS, MTS + 0.3, and MTS + 0.6 mph. Cross-correlation comparisons and discrete parameters of the EMG activity ensemble curves were examined across trials and conditions. Two factor (condition and trial) repeated measures ANOVA was employed for statistical analysis ($\alpha = .05$). For the correlation parameters, significant running condition/trial interactions were observed for all muscles. Significant condition/trial interactions were revealed for the discrete parameters concerning activation magnitude (GM, RF, VL, TA, GAS, and SOL).
and duration (RF, GAS, and SOL) for both walking and running. EMG activity intensity and
duration in some muscles changed with the locomotion speed in a quadratic fashion, which was
only observed in transition related trials. These results indicate that neuromuscular changes
occurred steps before the observed gait transition and that changing velocity induces gait
transition related behavior that cannot be observed with constant velocity in the same range.
INTRODUCTION

Locomotion of multi-legged animals including human locomotion consists of parameters that interact with each other in particular ways to define the type (mode) of locomotion and its task-efficiency. Among the different spatial-temporal coordinates are distinct patterns of leg movements, gaits. Collins and Stewart (1993) provide descriptions of various animal gaits and evidence for symmetry and periodic, cyclic sequences associated with the gaits. Both quadrupedal and bipedal locomotion contain patterns in which the legs are in phase and out of phase. Two-footed hopping is considered an in-phase locomotion pattern, where walking, galloping, and running are recognized as out of phase patterns. Therefore when describing cyclic patterns, the reference frame (single foot, a pair, or all legs) needs to be defined. For single limb cycles, the interval between two contacts to the ground of the designated foot conventionally defines one stride cycle. Stride cycles are further defined by phases within the cycle, such as the reference foot in contact with the ground (stance phase) and the reference foot off of the ground (swing phase). For two limbs, when the reference foot and paired foot are simultaneously off of the ground, the animal is in flight phase and when they are simultaneously in contact with the ground, the animal is in double stance. For quadrupedal gaits, flight phase refers to all of the legs (double-flight) or pairings of legs being off the ground depending on the reference frame. In bipedal animals when describing gait according to both feet, the existence of double-stance and double flight phases often distinguishes between walking and running gaits.
With knowledge of differing gait characteristics, the effects of variables and accommodating mechanisms for those variables can be investigated. One such study conducted by Biewener and Gillis (1999) emphasized the role of muscle function in accommodation to animal locomotion within varying environments. They emphasized that changing the environmental conditions effects the underlying kinematic and kinetic characteristics of the animals’ locomotion. As such, the muscular activity alters to produce the required movement and force to facilitate locomotion or to transfer to another mode of locomotion within the new environment. The latter case introduces the general concept that animals are capable of multiple gaits. Moreover, animals tend to locomote within a small range of speed for each gait and switch to another gait or mode of locomotion if the animal moves out of the preferred speed range for a specific gait pattern. But, what is the etiology of animal, more specifically human, gait transitions and what role does the underlying lower extremity neuromuscular coordination play?

The following information on gait transition mechanisms and neuromuscular gait patterns addresses these questions. Gait transition mechanisms are presented as they relate to different animal gaits and their application to human gaits. Information regarding neuromuscular patterns is provided according to humans walking and running at preferred speeds as well as locomoting at transition speeds. In preparation for the discussion on neuromuscular patterns, a brief review of electromyography (EMG) patterns is provided.
Gait Transition

One of the first hypothesized mechanisms associated with gait transitions deals with energy optimization of the system (Alexander, 1989). The theory suggests that gait transitions occur in an effort to decrease the energy cost of locomotion. In support of the optimizing mechanism, kinematic and kinetic factors such as kinetic energy (Turvey, Holt, LaFiandra, & Fonseca, 1999) of the gait have been investigated in an attempt to clarify the relationship between mechanical and metabolic gait components. Tuvey et al. (1999) successfully uses these factors to predict running metabolism and run to walk transition speed, which provides recent support for relating energetic factors to gait constraints. However, evidence refuting the significance of energetic factors on gait transitions also exists. At least, gait transitions are not the result of an energy saving mechanism alone (Brisswalter & Mottet, 1996; Farley & Taylor, 1991; Hreljac, 1993). Other mechanisms relating to kinematic (Hreljac, 1994), kinetic, and anthropometric (Hreljac, 1995) factors have been proposed along with empirical evidence. In some conditions, this energetically optimizing trigger is muted by the requirement of other mechanisms (Farley & Taylor, 1991). A more detailed review of Farley and Taylor (1991), Hreljac (1993), and Brisswalter and Mottet (1996) shall further elaborate the preceding statement. Farley and Taylor report that trot to gallop transitions occur in horse locomotion when the peak stresses applied to the musculature and bones of the horses rises to a critical level. With the application of these critical forces, horse gait switches to a mode with less peak force levels (in this case, from trot to gallop). The speed at which the horses transfer actually requires more energy. Within humans, the progression from walk to run (WR) and run to walk (RW) is also not
solely dependent on energy cost optimization (Brisswalter & Mottet, 1996; Hreljac, 1993). During WR, Brisswalter and Mottet find that the preferred gait transition speed of their subjects is significantly different than transfer speeds that are energetically optimized. However in contrast to empirical evidence regarding horses, empirical evidence also suggests that human gait transition is not solely dependent on peak stresses either, since running actually increases stress after the walk to run transition (Nilsson & Thortenson, 1989). So, are human gait transitions regulated by optimizing energetic triggers, mechanical triggers, a combination of both mechanisms, another mechanism not previously discussed, or some combination thereof?

Perhaps a dynamical systems approach, as recommended by Brisswalter and Mottet (1996) and others (Li, van den Bogert, Caldwell, van Emmerik, & Hamill, 1999), could be used to better describe locomotion mechanisms and could better predict the various parameters related to gait transition. Brisswalter and Mottet find that stride length variability increases before reaching the preferred walk to run and run to walk transition speeds. Such a system behavior is a prediction characteristic associated with non-linear dynamic systems. In applying such an approach, gait transitions become the shifts (bifurcations) that attractor states such as walking and running experience when a control parameter (such as velocity) is manipulated and locomotion itself is a self-organizing system. Recent support to the non-linear behavior of gait transitions shows a quadratic trend in relation of vertical ground reaction forces to locomotion speed as approaching toward gait transition (Li & Hamill, 2001).
Neuromotor Coordination

Regardless of which approach is taken in describing gait transitions, it is known from animal studies that neuromotor patterns change in respect to gaits (Biewener & Gillis, 1999; Gray, 1968; Heglund, Fedak, Taylor, & Cavagna, 1982; McMahon, 1984). Through the use of surface EMG, these changes are investigated in humans. EMG represents the neurological stimulation of the muscular activity and is the algebraic summation of the action potentials of the recruited motor units. EMG does not directly represent the muscular force or type of contraction triggered by the activation. Even EMG has its limitations, and previous research and current technology provide techniques and procedures so EMG results could be used to study neuromuscular coordination during locomotion (Acierno, Baratta, & Solomonow, 2000; Shiavi, Frigo, & Pedotti, 1998; Winter, 1991).

The literature provides abundant descriptions of the lower extremity muscle functions during walking and running (Annaswamy, Giddings, & Della Croce, 1999; Jacobs, Bobbert, & van Ingen Schenau, 1993; Mann, Moran, & Dougherty, 1986; McClay, Lake, & Cavanagh, 1990; Nene, Mayagoitia, & Veltink, 1999; Nilsson, Thorstenson, & Halbertsma, 1985; Prilutsky & Gregor, 2001; Prilutsky, Gregor, & Ryan, 1998; van Ingen Schenau, 1989; Winter, 1991). For the purpose of this study, only seven muscles were investigated. The following section introduces the seven muscles in terms of their EMG patterns, suggested functions in walking and running, and prospective differences between the two gaits, which are also further defined. In addition, Figure 1.3 displays the muscles’ EMG activity durations for walking and running over the entire gait cycle. The investigated muscles include monoarticulate and bi-articulate muscles, proceed proximally to distally, and include agonists and antagonists pairs. The literature suggests that monoarticulate muscles mainly generate positive work for the movement while bi-articular muscles control net joint movement and work (Jacobs et al., 1993; van Ingen Schenau, 1989).
**Walking**

In examining the movement cycle of one designated leg, human walking consists of two phases, stance and swing, separated by heel contact (HC) and toe off (TO) respectively. Stance phase ends with TO (an event in which the support foot’s toe is no longer on the ground), which also initiates swing phase. Swing phase ends at the next heel contact of the designated limb. In terms of cycle duration, stance phase occurs from 0% to approximately 60% of the cycle with weight acceptance (WA) at the first 10% of the stride and preparation for toe off (push off) occurring from approximately 40% to 60% of the stride. Since consequent HC's of the same designated foot denote the cycles, HC are at 0 and 100% of the gait cycle. Swing phase begins at TO which is at approximately 60% of the stride cycle and ends with next HC. In regards to a more functional description, stance phase entails loading of body weight onto the support leg while the opposite leg moves forward and then entails preparing the support leg for forward propulsion and swing. Swing phase consists of the foot following through (foot clearance), the forward swing of the limb, and the lowering of the foot. In combining the motion of both limbs (Figure 1.1), the walking gait can be characterized by double stance (both feet on the ground) and single stance phase (one foot in contact). Single stance phase is present in most of the two-limbed reference of the gait cycle (nearly 80%) while double stance exists within the rest of the cycle.

**Running**

Similarly to walking, running consists of stance and swing phases that are also separated by HC and TO. However because of the shorter stance phase (approximately 35% of the gait cycle), running exhibits double flight instead of double stance. Since stance is considerably shorter, cyclic events occur earlier in stride as observed in TO but remain proportional in relation to each phase (Figure 1.2).
Figure 1.1: Walking Stride Cycle. Depicts the bipedal gait description of walking in reference to two feet. The specific stride characteristics of heel contact (HC) and toe off (TO) are referenced for both the left (L) and right (R) foot. The time between each HC and TO equates to stance, and the time between TO and the subsequent HC equates to swing phase. Each stance and swing phase refers to one stride cycle. Stance phase occupies more than half of the cycle. Particular to walking is double stance whose period is signified in red. Double stance occurs when the left and right foot are both in stance, and therefore are in contact with the ground.

Figure 1.2: Running Stride Cycle. Depicts the bipedal gait description of running in reference to two feet. The specific stride characteristics of heel contact (HC) and toe off (TO) are referenced for both the left (L) and right (R) foot. The time between each HC and TO equates to stance, and the time between TO and the subsequent HC equates to swing phase. Each stance and swing phase refers to one stride cycle. Swing phase occupies more than half of the cycle. Particular to running is double flight whose period is signified in blue. Double flight occurs when the left and right foot are both in swing, and therefore are not in contact with the ground.
Muscle Activity Patterns

(See Figure 1.3 for summary of all muscle activity patterns.)

Gluteus Maximus (GM), monoarticular muscle

For walking, major activity begins (onsets) late in the second half of swing phase, peaks during WA, and continues until mid-stance (Nilsson et al. 1985; Prilutsky & Gregor, 2001; Winter, 1991). While a second activity burst occurs during the first half of swing phase (Winter, 1991). Winter speculates that the major activity burst serves to extend the hip and thus control rotation at the hip and knee. To further elaborate, during weight acceptance, hip extension by the GM contraction assists in decelerating forward thigh rotation (momentum of the thigh) which was generated during swing, and since the GM actively controls this rotation, it also passively controls knee flexion caused by the loading of the support leg. Active control of knee flexion, however, requires knee extensor muscles. The role of activity at WA may also include stabilizing the pelvis so spinal extensors can decelerate the forward trunk rotation. In this instance, the GM activity prevents forward translation of the pelvis by the spinal extensors. Winter also suggests that the smaller activity period functions to decelerate the forward swinging thigh and even reverse thigh direction at 85% of stride, despite the limb being in swing phase. This minor activity period is neither reflected in running EMG patterns nor reported by Nilsson et al. (1985). Only activity initiating at late swing and continuing through early stance appears in running (Mann et al., 1986; McClay et al., 1990; Nilsson et al., 1985). The suggested functions of this burst consist of stabilizing the pelvis and thigh at HC in cooperation with other muscle groups while initializing hip extension for early stance and decelerating the thigh through eccentric contractions during late swing (Mann et al., 1986; McClay et al., 1990; Nilsson et al., 1985). Walking appears to involve earlier and more thigh deceleration then running since increasing gait speed is related to hip flexion and knee extension activity (Mann et al., 1986).
**Biceps Femoris, lateral aspect of the long head (BF), bi-articulate muscle**

This hip extensor and knee flexor muscle demonstrates two activity periods for walking with differing magnitudes as reported by Winter (1991). The major burst begins in middle swing phase and peaks early in stance (4% of stride). The second smaller burst occurs just after TO, early in the swing phase. At mid-swing, the BF flexes the knee to decelerate the swinging lower limb (segment rotation about the knee). The need for deceleration arises from a reversal in the thigh direction caused by hip extensors. As activity continues into stance phase and peaks near WA, the BF serves as a hip extensor in conjunction with the GM to decelerate forward thigh rotation and stabilize the pelvis during weight acceptance. Winter excludes mentioning possible functions for the minor period. Interestingly, several researchers mention BF with GM in decelerating hip rotation (during mid-swing) caused by the hip flexors and knee extensors for running modes (McClay et al., 1990). And as mentioned in discussing GM functioning, the minor burst observed in walking may be related to early hip extension during swing phase since this mode does not require as much propulsion as running (Jacobs et al., 1993). Within the perspective of these gait differences, researchers stress different primary roles for BF despite the generalizable EMG patterns. Winter speculates hip extension and the provided joint stability during weight acceptance of walking as a more important role in walking. While, McClay et al. stress deceleration of hip rotation through concentric extension at that joint and deceleration of the lower limb rotation about the knee through concentric flexion as a more primary role in running. Upon closer investigation into the running swing phase activity of BF, Prilutsky et al. (1998) report more significant activity during late swing phase than during early swing phase. They offer that the coordination between the hamstrings (BF included) and the quadriceps (particularly rectus femoris) reduces muscle fatigue experienced in the swing phase of running.
Figure 1.3: Activity Duration & Limb Segment Movement Estimates. Summarizes the cyclic activity (duration) of various muscles of the lower extremities during walking and running and provides stick figure depiction of net muscular forces on the segments. Blue horizontal bars depict running phasic activity. Red bars represent walking activity. The red stick figures and blue stick figures represent walking and running, respectively. The purple arrows depict extensor or flexor group moments of the segments. The horizontal axis references the stride cycle with heel contact (HC) events at 0% and 100% and with toe off (TO) events at 35% and 60% stride for running and walking respectively (Annaswamy, Giddings, & Della Croce, 1999; Jacobs, Bobbert, & van Ingen Schenau, 1993; Mann, Moran, & Dougherty, 1986; McClay, Lake, & Cavanagh, 1990; Nene, Mayagoitia, & Veltink, 1999; Nilsson, Thorstenson, & Halbertsma, 1985; Prilutsky & Gregor, 2001; Prilutsky, Gregor, & Ryan, 1998; van Ingen Schenau, 1989; Winter, 1991).
**Vastus Lateralis (VL), monoarticulate muscle**

During walking, this quadrecip-member activity starts at 95% of stride and ends at mid-stance, approximately 30% of stride (Nilsson et al., 1985; Prilutsky & Gregor, 2001; Winter, 1991). Winter speculates that VL extends the knee during WA to counter knee flexion and stabilize the knee as the weight is added. If the knee is not stiffened and left pliant, the addition of weight would cause the knee, and thus the limb, to collapse. After WA, the limb continues to translate and rotate forward, so knee extension continues through midstance, when knee flexors and hip extensors resume activity to decelerate the limb and initiate swing (Winter, 1991).

Another possible activity period is present, occurring just after TO. VL may be assisting other quadriceps in bracing the leg and foot at the knee from backward swinging (Winter, 1991). The literature reports similar pattern observations in running with more occurrence of the second burst then when observed in walking (McClay et al., 1990; Nilsson et al., 1985). Hence, suggested functioning roles do not differ between walking and running.

**Rectus Femoris (RF), bi-articulate muscle**

Several researchers (Annaswamy et al., 1999; Mann et al., 1986; Nene et al., 1999; Nilsson et al., 1985; Prilutsky & Gregor, 2001; Winter, 1991) provide descriptions for EMG patterns and for possible roles of this hip flexor and knee extensor. A first RF activity period resembles VL in that it is active before HC (late swing phase), continues into stance phase, peaks at WA, and ends during midstance. Also in comparison to VL, the second burst of activity occurs just after TO but not for the same suspected role. While active in late swing phase (first activity period), RF possibly extends the leg and foot in preparation of HC and, in conjunction with other quadriceps (VL), is stabilizing the knee from the addition of weight on the support leg and then
continuing knee extension until midstance. The second burst during walking is suspected to consist of hip flexion in addition to knee extension. These studies further speculate that the hip flexion contributes to the forward translation and swing of the limb while the knee extension contributes to the backward swing of the leg and foot segments. As such, RF is redirecting some of the work generated by hip flexion to the knee joint in order to counter-act the kinematic and kinetic consequences (*i.e.*: backward rotation of the leg and foot segments) of conducting forward swing (Nene et al., 1999). For running activity, RF is suggested to serve the same hip flexion/knee extension functioning (second burst) as it did in walking (Nilsson et al., 1985; Prilutsky et al., 1998). In Prilutsky et al., their study reports that running activity of the RF during swing phase consists of varying activity, in which greater activity is observed during early swing. To recall, this difference mirrors the findings of the BF (later swing activity more significant). Running EMG patterns do show activity in late swing (first burst), which proceed into the stance phase similarly to walking. However, this activity appears earlier then its walking onset. Perhaps since the stance phase is shortened in running, quicker foot placement is required thus an earlier onset is observed (Mann et al., 1986; McClay et al., 1990; Nilsson et al., 1985).

**Tibialis Anterior (TA), monoarticular muscle**

Observations of walking EMG patterns contain two noted activity periods (Nilsson et al., 1986; Winter, 1991). The major activity burst onsets at the end of swing phases, peaks immediately after HC, and then decreases until offset near midstance. The second walking burst onsets at TO and continues into mid to late swing phase. These two studies suggest that TA serves to position the foot and more specifically the heel through dorsiflexion, for ground contact when activating in late swing phase and continuing into HC. When TA activity peaks at HC,
flexion of the ankle may assist in stabilizing the ankle from opposing ground reaction forces (impact is absorbed at the heel instead of the majority of the foot). The TA minor burst close to TO may pull the leg over the foot and after TO may dorsiflex the foot to clear the ground (Nilsson et al., 1985; Winter, 1991). In contrast to walking, the activity of the TA preceding TO and prior to TO is much more prevalent in running. Nilsson et al. note that some of their participants demonstrate bimodal tendencies for only one continuous activity period instead of complete onset and offset for two separate activity periods, as in walking. McClay et al. (1990) suggest that the increased activity at the vicinity of TO, which may serve in the same leg rotation/foot clearance role as walking, may be functionally enhanced by TA eccentric contractions at or before HC. Note, however, at toe off the lower extremity swings forward during walking and swings backwards during running. Observationally, the spatial position of the foot during and at HC denotes ankle angular magnitudes relative to the leg and the foot segments as being greater in running then walking, so the strict placement of the heel at first contact is lessened (Nilsson et al., 1985). However, this work may not be the result of TA eccentric lengthening as McClay et al. suggest. A bi-articulate dorsiflexor (gastrocnemius) and its monoarticular agonist (soleus) are also active at this time in running, and the estimated TA lengthening may be the passive result of these muscles’ activities. In consideration of this case, the co-activation of TA and the dorsiflexors before and at HC may serve to stabilize the ankle joint, while the additional work capability of the TA before TO and during TO results from theoretical bi-articulate functioning (van Ingen Schenau, 1989). Further discussion of this suggested effect is presented later.
Gastrocnemius, lateral (GAS), bi-articulate muscle

The bi-articular (knee flexor and ankle plantar flexor) GAS has only one major activity period, which onsets just prior to HC, peaks at 50% of stride, decreases during the remainder of stance phase, and plateaus or possibly increases at TO, after which it maintains low activity level throughout the rest of the gait cycle (Nilsson et al., 1985; Prilutsky & Gregor, 2001; Winter, 1991). Nilsson et al. describes GAS activity patterns as occurring out of phase with TA activity. According to these study estimations, the GAS lengthens to eccentrically control forward rotation of the leg after HC when TA is supposedly quiet. In effect, the GAS decelerates leg velocity through knee flexion and may also be contributing to joint stability as contact is made. When the activity peaks, GAS transfers the potential energy gained from active lengthening to kinetic energy for push-off as suggested by Winter. The GAS is estimated to shorten and cause plantar flexion of the ankle. The immediate drop in activity after this peak is observed as the cycle nears TO which is of interest since a second TA activity burst occurs at TO, where forward translation of the leg over the foot is supposedly controlled by the TA. A. The remaining low activity level during swing is presumably for knee flexion in coordination with RF and VL. The reciprocal pattern coordination between GAS and TA is not seen in running (Nilsson et al., 1985; McClay et al., 1990). Instead, the GAS activity starts in late swing and subsides during mid to late stance. The earlier onset and activity occurring during late swing is associated with co-activation of TA and is suggested to decelerate ankle forward rotation resulting from swing and muscular work for foot clearance (Nilsson et al., 1985; McClay et al., 1990). The ankle plantar flexion present at this point is in antagonism to the TA, which theoretically should passively lengthen unless that muscle produces an equal or greater reaction (van Ingen Schenau, 1989).
Jacobs et al. (1993) and Mann et al. (1986) estimate an increase in GAS length just before and during HC, resulting from eccentric based knee flexion that may serve to decelerate leg forward rotation along with BF (Nilsson et al., 1985; McClay et al., 1990). According to theoretical bi-articulate functioning (van Ingen Schenau, 1989; Jacobs et al., 1993), BF, RF, and GAS are controlling net joint movements of the hip, knee, and ankle and transporting the mechanical work of the monoarticulate muscles to accomplish walking or running. The lengthening of the GAS increases potential mechanical energy, which converts to mechanical energy (as the GAS concentrically plantar flexes the ankle) and controls the net movements about the ankle to which the TA contributes. Van Ingen Schenau demonstrates possible effects of not controlling for TA work (forward joint rotation) through the use of a segmented, cardboard model that utilizes springs to produce mechanical work and joint moments. He generalizes the model’s segment, joint, and spring behaviors to human muscular coordination. When not constraining the ankle with a wire (knee extensor/ankle plantar flexor), net joint power in the knee increases while ankle net movements cause the foot to lose contact with the ground before an appreciable amount of forward translation can occur. Although his investigation did not include running push-offs, a follow-up study conducted by Jacob et al. does investigate running, providing supporting evidence in the application of bi-articulate functioning to running. Therefore, GAS activity and the co-activity of GAS with TA after HC and before TO may be applied to this theory and explained functionally as plantar flexing the ankle to generate forward translation (propulsion) and to maintain foot contact during the generation of propulsion, effecting the net joint moment of the ankle (Nilsson et al., 1985; McClay et al., 1990; Jacobs et al., 1996).
Soleus (SOL), monoarticular muscle

Walking EMG pattern consists of activity level during stance, peak activity level at mid to late stance (push-off), and the activity burst ended approximately after TO (Winter, 1991). Speculatively, activity level during stance is to plantarflex the ankle, initially decelerating to a degree forward rotation of the leg and then to assist GAS in generating push-off at 40-50% of stride (Winter, 1991). McClay et al. (1990) combine GAS and SOL running EMG patterns and possible functionality; so according to their review, SOL initiates in late swing and peaks during running push-off (approximately 20-30% of stance phase). The main function would be propulsion at push-off. However, a distinction is required between the two muscles (GAS and SOL). Since SOL does not articulate the knee, its activity during swing is not associated with knee extension and plateaus during early stance (Jacobs et al., 1996), when GAS is using knee extension to decelerate forward leg rotation.

The above descriptions only provide possible explanations of muscle activity during stable speeds and as such do not mention whether changes in muscular function and pattern (activity onset, duration, and peak) exist at transition speeds and in speeds approaching the transition speed. Unfortunately, only two studies to date investigate changes in muscle activity in human walking and running close to gait transition speeds. Nilsson et al. (1985) and Prilutsky and Gregor (2001) report the presence of differences among muscle activity patterns in participants as speed changes within each locomotion mode, and support the presence of muscular pattern coordination differences between each locomotion mode. The reported differences (coordination pattern changes within a specific mode) occur when walking or
running gaits are maintained past the respective gait transition speeds. These studies call for walking or running at various magnitudes of speed including the participants’ preferred transition speeds and several speeds of greater and lesser magnitude than the transition speeds. The previous transition related studies (Nilsson et al., 1985; Prilutsky & Gregor, 2001) collect EMG data of walking and running at extremely variable speeds as compared to the normal range of speeds in which the modes occur. Their results seem to support dynamical system-based predictions as presented by Brisswalter and Mottet (1996), in which muscular patterns at speeds near transition (before and after) should vary non-linearly. However due to the constraints of the protocol, the previous transition related studies (Nilsson et al., 1985; Prilutsky & Gregor, 2001) could not provide detailed information regarding how the lower extremity coordination changes as approaching gait transitions.

Therefore, the purpose of this study was to further investigate the transition process and quantify the differences of muscular coordination during continuously changing speeds as approaching to gait transitions. More specifically, the following hypotheses and supporting arguments are submitted. If nonlinear behavior exists as locomotion nears transition, then it would reason that, in relation to muscular coordination, significant differences between stable locomotion and transition locomotion should be observed and are better represented within continuously changing speed conditions than differing constant speed conditions. Li and Hamill (2001) present evidence concerning speed condition 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 are made as the
participants’ speed continuously changed via (+/-) constant acceleration, producing gait transitions during the collection interval. Results for these experimental conditions resemble previous literature findings (Nilsson & Thorstensson, 1989) in that VGRF characteristics differ as locomotor speed changes, and the results provide a more specialized analysis of the steps preceding the transition point. Within these steps (5 steps before transition point) non-linear trends are reported for VGRF and for the interactions between the pre-transition steps and acceleration. Hence, it was important to this study’s methodology to analyze pre-transition coordination within at least five steps before the transition speed.
METHODOLOGY

Participants

The experimenter recruited twelve adults, 18-41 years of age, from the community of Louisiana State University. Informed consent was obtained; any exclusion was based on pre-existing gait dysfunctions. Descriptive statistics are reported in Table 2.1.

Table 2.1: Descriptive Statistics of Participants.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Gender</th>
<th>Age (years)</th>
<th>Mass (Kg)</th>
<th>Stature (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>M</td>
<td>41</td>
<td>95.5</td>
<td>185.4</td>
</tr>
<tr>
<td>2</td>
<td>F</td>
<td>19</td>
<td>63.2</td>
<td>167</td>
</tr>
<tr>
<td>3</td>
<td>M</td>
<td>24</td>
<td>79.5</td>
<td>172.7</td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>30</td>
<td>100</td>
<td>182.9</td>
</tr>
<tr>
<td>5</td>
<td>M</td>
<td>24</td>
<td>75</td>
<td>170.2</td>
</tr>
<tr>
<td>6</td>
<td>M</td>
<td>26</td>
<td>87.3</td>
<td>172.7</td>
</tr>
<tr>
<td>7</td>
<td>M</td>
<td>22</td>
<td>84.1</td>
<td>177.8</td>
</tr>
<tr>
<td>8</td>
<td>F</td>
<td>20</td>
<td>48.6</td>
<td>157.5</td>
</tr>
<tr>
<td>9</td>
<td>M</td>
<td>21</td>
<td>84.1</td>
<td>180.3</td>
</tr>
<tr>
<td>10</td>
<td>F</td>
<td>20</td>
<td>63.6</td>
<td>167.6</td>
</tr>
<tr>
<td>11</td>
<td>M</td>
<td>24</td>
<td>97.7</td>
<td>198.1</td>
</tr>
<tr>
<td>12</td>
<td>M</td>
<td>24</td>
<td>87.3</td>
<td>188</td>
</tr>
<tr>
<td>Mean</td>
<td>--</td>
<td>21.8</td>
<td>77.6</td>
<td>178.2</td>
</tr>
<tr>
<td>SD</td>
<td>--</td>
<td>1.8</td>
<td>18</td>
<td>14.4</td>
</tr>
</tbody>
</table>

All participants, 9 males and 3 females, were recruited from the Louisiana State University campus. Gender, age, mass, and stature are reported in the columns. The last two rows report the mean and standard deviation (SD) values for the subjects’ age, mass, and stature.
Materials

**Kistler Gaitway™ Treadmill**

The treadmill (Kistler, Amherst, NY), which was motor driven, allowed for level locomotion and speed control of the subject. Varying the treadmill’s speed allotted for the testing conditions to be examined. The treadmill also provided safety measures such as support railings without interference, *i.e.* the railings did not block the participants’ movements from the recording camera.

**MotionAnalysis™ System**

The system was designed for two-dimensional (2-D) biomechanical analysis (MotionAnalysis, Santa Clara, CA). Included with the system was a digital camera; an AMTI™ force platform (Advanced Mechanical Technology, Inc., Watertown, MA); a sixteen-channel MA-300-16 EMG System© (surface electromyography system) (Motion Lab Systems Inc., Baton Rouge, LA).

**Infrared Video Camera**

The system included a camera with infrared lights surrounding the lens. The infrared light was reflected off of subjects’ markers, positioned in the sagittal plane, and captured by the camera’s lens. A calibration cube frame set and calibrated the camera’s recording field.

**The EMG System**

Specifications consisted of ± 5 volts full scale EMG signal output level, of 20 to 2000 Hz at –3 dB standard EMG bandwidth, of a built in low pass filter, of an electric isolation capability of 600 volts DC, and of a 60 feet RG-174 cable at 3mm diameter for signal connection to a desktop interface unit.
Electrodes/Preamplifier: Consisted of a single, modular, surface-mount pre-amplifiers with full static and muscle stim protection and four dry button pre-amplifier contacts. The contacts were approximately 2 cm apart at the center of each button. The pre-amplifier was connected to a backpack with ten gain settings via a single, highly flexible six-pin Harwin connector. The pre-amplifiers were placed on the participant’s skin, directly over the muscular bellies, with the same adhesive tape used for the markers. Abrading the skin was not required.

Back-Pack/Amplifier: A sixteen-channel amplifier with a gain range of 20-20,000 optimized the EMG signal. For this study, only seven channels were used. The backpack was attached to an adjustable, pliable belt which was fastened according to the subject’s preference around the waist.

Procedure

The experimenter divided the conditions into two sections depending on the manipulation required of the treadmill speed. Both sections required placement of the markers and electrodes, therefore the initial procedures of both section protocols were similar; only the application of speed and the number of trials differed.
**Experiment Preparation**

Before each testing section, the MotionAnalysis™ system was calibrated and prepared for data collection. The tester set the infrared camera sampling frequency at 60Hz and synchronized the EMG system to 960Hz. With the arrival of the participants, reflective markers and surface electrodes were placed on the respective anatomical landmarks:

- **Hip Marker**: Head of the greater trochanter.
- **Knee Marker**: Joint midline, as determined from locating the lateral tibia condyle and systematically progressing to the knee joint midline.
- **Ankle Marker**: Lateral malleolus of the tibia.
- **Heel Marker**: The calcaneus.
- **5th Metatarsal Marker**: The 5th metatarsal-phalange joint.

More specifically, the participants were asked to contract and relax the muscle, while the experimenter located the muscle belly. Once the desired area for the electrode pair was established, the experimenter adhered the electrode pair to the skin parallel to the muscle fibers. Moderate tape wrapping at the locations of the electrodes and the wires of the electrodes reduced movement artifact. This procedure was repeated for all of the muscles. Again, the seven muscles to be studied were chosen based on functionality, antagonistic role, and articulation role (Table 2.2).
Table 2.2: Muscle Breakdown and Anatomical Function.

<table>
<thead>
<tr>
<th>Muscles</th>
<th>Joints</th>
<th>Flexion</th>
<th>Extension</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Gluteus Maximus</em> (GM)</td>
<td>Hip</td>
<td>N/A</td>
<td>√</td>
</tr>
<tr>
<td><em>Rectus Femoris</em> (RF)</td>
<td>Hip</td>
<td>√</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Knee</td>
<td>N/A</td>
<td>√</td>
</tr>
<tr>
<td><em>Vastus Lateralis</em> (VL)</td>
<td>Knee</td>
<td>N/A</td>
<td>√</td>
</tr>
<tr>
<td><em>Biceps Femoris</em> (BF)</td>
<td>Hip</td>
<td>N/A</td>
<td>√</td>
</tr>
<tr>
<td>long head</td>
<td>Knee</td>
<td>√</td>
<td>N/A</td>
</tr>
<tr>
<td><em>Tibialis Anterior</em> (TA)</td>
<td>Ankle</td>
<td>√</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Dorsiflex)</td>
<td></td>
</tr>
<tr>
<td><em>Gastrocnemius</em> lateral head (GAS)</td>
<td>Knee</td>
<td>√</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Ankle</td>
<td>N/A</td>
<td>(Plantarflex)</td>
</tr>
<tr>
<td><em>Soleus</em> (SOL)</td>
<td>Ankle</td>
<td>N/A</td>
<td>(Plantarflex)</td>
</tr>
</tbody>
</table>

The seven muscles investigated in this study are listed in rows with the joint and anatomical function listed in columns. Distinction of the specific muscle head for the biceps femoris (BF) and gastrocnemius (GAS) is also provided. A check mark signals which function, flexion or extension, the muscle preformed.

Once all electrodes were in place, the experimenter adjusted the amplifier gain for each channel in reference to the respective signal displays in order to optimize the signal output.

Figure 2.1 exemplifies the EMG signal output based on actual participant data. During this stage, the participant warmed up on the treadmill for approximately five minutes during which any signal, location, and gain adjustments were made. The initial accommodation warm-ups were conducted for walking at 3.0 mph. The final warm-up/adjustment periods included running at 6.0 mph.
Since one of the purposes of the study was to better investigate coordination changes during gait transitions, prior protocol strategies needed to be conducted along with the more experimental protocol. Therefore, four different conditions were designed among which two different protocols were required to test the conditions. The first protocol, continuously changing speeds (CCS), allowed for collection during the gait progressions. The type of progression constituted the condition. As such walking to running (WR) and running to walking (RW) were considered conditions. The second protocol, constant speed ranges (CSR), resembled the previous interval speed-based studies (Prilutsky & Gregor, 2001; Nilsson et al., 1985). For this protocol, the experimenter conducted trials across both gaits in which the gait being tested constituted the condition. Hence a walking condition (WC) and a running condition (RC) were designated. Since one of the observations from the CCS protocol was required to formulate the speeds tested in the CSR protocol, CCS is presented first.

**Figure 2.1: Raw Signal Graph.** Depicts the EMG signal output of the soleus (SOL) for the first trial of the walking at constant velocity condition (WC1) for subject 4. The A/D board setting and gain setting allowed for the signal to be optimized and recorded.

Protocols

Since one of the purposes of the study was to better investigate coordination changes during gait transitions, prior protocol strategies needed to be conducted along with the more experimental protocol. Therefore, four different conditions were designed among which two different protocols were required to test the conditions. The first protocol, continuously changing speeds (CCS), allowed for collection during the gait progressions. The type of progression constituted the condition. As such walking to running (WR) and running to walking (RW) were considered conditions. The second protocol, constant speed ranges (CSR), resembled the previous interval speed-based studies (Prilutsky & Gregor, 2001; Nilsson et al., 1985). For this protocol, the experimenter conducted trials across both gaits in which the gait being tested constituted the condition. Hence a walking condition (WC) and a running condition (RC) were designated. Since one of the observations from the CCS protocol was required to formulate the speeds tested in the CSR protocol, CCS is presented first.
Continuously Changing Speed, CCS

With all initial preparations met, the participant proceeded to the first session, which consisted of five periods with each period including both progression modes (WR and RW). For WR, data collection began after the participant walked on the treadmill for twenty seconds at 2.0 mph via a trigger prompt. While recording, the experimenter continuously accelerated the treadmill provoking a transfer to running; the display speed of the treadmill never exceeded 10.0 mph. The experimenter terminated treadmill acceleration after the WR transition. Total collection time was for 20 seconds although most transitions occurred within 10 seconds. The approximate transition speed was recorded. Systematically, the treadmill was decelerated back to the initial speed of 2.0 mph, and the participant returned to a stable walk. For RW, the treadmill was systematically accelerated until a stable running locomotion was observed around 6.0 mph and 7.0 mph and maintained for twenty seconds. This initial running speed was recorded. After the acclimation period, the experimenter began data collection and continuously decelerated the treadmill. The experimenter ended deceleration of the treadmill at 2.0 mph and recorded the approximate transition speed. Again the collection time was set at 20 seconds while the actual progression only took 10 seconds. A qualified collection for both conditions consisted of five observed left heel contacts prior to the transition which were considered to be trials. The testing order of the two types of transitions was balanced to avoid any order effects (Table 2.3). The mean transition speed of each participant was calculated before proceeding to the second session.
Table 2.3: Balanced Order Chart.

<table>
<thead>
<tr>
<th>SUB</th>
<th>1st</th>
<th>2nd</th>
<th>N</th>
<th>3rd</th>
<th>N-1</th>
<th>4th</th>
<th>N-2</th>
<th>5th</th>
<th>N-3</th>
<th>6th</th>
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<tr>
<td>1</td>
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<td>10</td>
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<tr>
<td>11</td>
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<td>5</td>
<td>9</td>
<td>6</td>
<td>8</td>
<td>7</td>
</tr>
</tbody>
</table>

Ten trials, five for walking and five for running were conducted according to the testing order of this chart for each subject for both sessions in order to avoid any order effects.

**Constant Speed Ranges, CSR**

This session entailed walking and running at set speed intervals for five trials. The speed range for each subject depended on the mean of the recorded transition speeds (MTS) from the preceding session (CCS). Interval speeds were determined from MTS as follows: (-) 0.6 mph value, (-) 0.3 mph value, MTS value, (+) 0.3 mph value, and (+) 0.6 mph value. For each speed interval, twenty seconds of acclimation occurred, followed by ten seconds of data collection, then twenty seconds of rest. The experimenter safely slowed and stopped the treadmill before initiating the rest period. Each trial was a walking or running interval (five trials for each gait). Balancing of the ten different tests again avoided any potential order effects (Table 2.3).
Data Processing

Data processing served to standardize and normalize the results for extrapolation of the variables to be used in statistical analyses. Of interest to the study were activity pattern variables, the original coefficient of cross correlation (R₀); the maximum coefficient of cross coefficient with phase shifting (Rᵢ); the difference between these two coefficients (Rₐᵢdiff); the shifting value (Percent), and discrete variables, onset; offset; duration; peak signal magnitude (PeakM); timing of the peak (PeakT).

Treadmill Speed Reliability

Kinematic measures were abstracted from discrete temporal points of the testing period (stance phase as determined by heel contact and toe off events) to ascertain more accurate measurements of the belt’s speed and whether the change in the display speed was representative of the belt. The following formula was applied to the five discriminated steps/trials prior to the transition step for all progression data collections, and Table 2.4 summarizes the average belt speed change over the trials.

\[
SV = \frac{\Delta X}{\Delta T}
\]

Where SV represents the stance phase velocity, \(\Delta X\) represents the change in the horizontal position of the participant’s foot when in contact with the treadmill belt or when in stance phase, and \(\Delta T\) represents the change in time during stance phase. Since stance phase is defined as the period from heel contact to toe off, the horizontal distance traveled begins at heel contact and ends at toe off. Therefore, the velocity formula is redefined as:
\[ SV = \frac{X_1 - X_2}{T_1 - T_2} \]

Where \( X_1 \) represents the horizontal coordinate of the heel marker at heel contact, \( X_2 \) represents the horizontal coordinate of the 5th metatarsal marker at toe off, \( T_1 \) represents the point time of \( X_1 \), and \( T_2 \) represents the point time of \( X_2 \).

**Table 2.4: Treadmill Speed Trend.**

<table>
<thead>
<tr>
<th>Condition Progressions</th>
<th>Desired Speed Change</th>
<th>Trial 1 (mph)</th>
<th>Trial 2 (mph)</th>
<th>Trial 3 (mph)</th>
<th>Trial 4 (mph)</th>
<th>Trial 5 (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run to Walk</td>
<td>Decelerate</td>
<td>4.65</td>
<td>4.45</td>
<td>4.25</td>
<td>4.00</td>
<td>3.72</td>
</tr>
<tr>
<td>Walk to Run</td>
<td>Accelerate</td>
<td>1.85</td>
<td>2.09</td>
<td>2.48</td>
<td>2.97</td>
<td>3.42</td>
</tr>
</tbody>
</table>

Average speed (mph) for each trial during stance phase is reported. During stance phase, the subjects’ foot was in contact with the treadmill belt and translated through space via the moving belt. As such the speed of the foot while in contact with the belt represents the belt’s speed. For run-to-walk progression, the mean trial speeds decreased. For walk-to-run progression, the mean trial speeds increased.

**Kinematic Data**

All kinematic data collected during the sessions were tracked by the MotionAnalysis\textsuperscript{TM} software to allow for marker identification, previewing of errors associated with faulty collection, and conversion of the data from binary to ASCII format. The ASCII files were processed through Microsoft Excel\textsuperscript{©} and converted to that program’s format for analysis and graphics.
Plotting the vertical coordinate displacement of the heel marker and the 5\textsuperscript{th} metatarsal marker in all collection periods aided in finding the participants’ strides. As graphed in Figure 2.2, the lowest vertical position of the heel marker, when graphed by time, represented the heel contact event of a stride cycle. The 5\textsuperscript{th} metatarsal marker, as depicted in Figure 2.3, approximately represented the toe off event of the stride cycle. Arguably, when the vertical coordinate of the 5\textsuperscript{th} metatarsal marker moved in an upward direction after reaching its most downward position, toe off was occurring. (Note: The toe did not leave the ground simultaneously with the 5\textsuperscript{th} metatarsal.)

In the case of CCS, the heel contact events (Figure 2.2), toe off events (Figure 2.3), and times of contact for five strides preceding the transition step were noted. Since stride characteristics of walking and running differed, the toe off and heel contact events for each gait changed. When the entire progression was graphed as in Figure 2.4, an observable pattern change in both marker displacements signified the transition step. And in the case of CSR, five strides occurring during the middle of the collection period were noted. Sections of all the EMG patterns (linear envelopes) were extracted based on the recorded heel contact times of the kinematic data.
**Figure 2.2: Heel Contact.** Depicts the y-coordinates for the heel marker for subject 10 during the third trial of the walk-to-run progression condition (WR3). The circled areas of the plot occur at the lowest vertical distance traveled by the heel marker. The ground hindered any further downward translation. Hence, the heel contacted the ground and remained in contact until the marker began upward translation again.

**Figure 2.3: Toe Off.** Depicts the y-coordinates for the 5th Metatarsal marker for subject 10 during the third trial of the walk-to-run progression condition (WR3). The circled areas of the plot occur at the initial upward translation of the marker after reaching the lowest vertical distance, which corresponded to heel contact. Hence, the foot contacted the ground and then lifted off of the ground, toe off.

**Figure 2.4: Progression for Walking to Running.** Depicts the kinematic graph of the y-coordinates for the heel and 5th metatarsal markers for subject 10 during the third trial of the walk-to-run progression condition (WR3). The heel contact and the toe off of the subject were plotted while speed increased inducing a walk-to-run transition. Based on the changing shape of the foot’s vertical displacement, the transition step was determined, from which the preceding five step (Steps –5 to –1) were defined.
EMG Profiling

For each EMG signal, a linear envelope which represented the profile was prepared; Figures 2.5-2.7 pictorially demonstrate the enveloping process. Signal biasness was removed through full-wave rectification, in which the mean of the raw signal data was calculated and used to find the deviation of signal data. Finding the absolute values of the deviated signal completed the rectification, and filtering the rectified signal completed the linear envelope.

Figure 2.5: Full-Wave Rectified EMG Profile. Depicts the EMG profile of the soleus for subject 4 during the first walking trial at constant velocity (W1). Formed by calculating the deviation of all data points from the mean and finding the absolute value of the deviated points.

Figure 2.6: Linear Envelope. Depicts the linear envelope of the soleus for subject 4 during the first walking trial at constant velocity (W1). Formed by passing the full-wave rectified data through a Butterworth, low pass filter with zero lag and cut off frequency of 6 Hz, as determined through residual analyses.
Residual analysis determined the cut off frequency of the filtering and followed procedures used by Winter (1990). For the analysis, the rectified EMG signal for several collection periods across all muscles was compared to several filtered versions of the same signal. Through graphing the residuals (Figure 2.8) or the difference between the signals, the presence of noise was evaluated and a cutoff frequency chosen. The following formula determined the residuals:

$$R(f_c) = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (X_i - \hat{X}_i)^2}$$

Where $N=$ number of sample points; $X_i =$ Rectified signal at $i$th sample; $\hat{X}_i =$ filtered signal at the $i$th sample.
Figure 2.8: Residual Analyses Graph. Depicts the residual plot for tibialis anterior of subject 4 during the first walking trial at constant velocity (W1). The vertical axis represents the residual values determined from the analyses of the full-wave rectified EMG profile (unfiltered) and the filtered profile, which was filtered by passing half the frequencies of the sampling frequency (960 Hz) through a Butterworth, 4th order, zero lag filter. The horizontal axis represents the cut-off frequencies. Theoretically, the more linear portion of the blue residual curve equates to the signal noise. By extending the linear slope (red line) of the residual curve, an estimate of the noise residual was made (the y-intercept of the red line). From the noise residual (y-intercept) a horizontal line (green) was extended to the curve. The point where these two lines intercept represented the best cut-off frequency for filtering the EMG signal. A green vertical line from this intercept point was drawn to better visualize the cut-off frequency. (Winter, 1990)
As a result of the residual analysis, a Butterworth, 4th order, zero lag, low pass filter set to pass the signal at a cut off frequency of 6 Hz was used for all signals.

With the smoothing and enveloping completed, the sections of the envelope that corresponded with the previously determined steps for CCS and strides for CRS were extracted by time frame and were normalized to a standard stride cycle, scaled at 100% of the stride cycle.

Ensembling of the normalized cycles further reduced the data for analyses. The ensembling for CCS occurred at the following levels. Each preceding step was ensembled across the repeated progressions with its respective step for all muscles and subjects. The averaged steps were now considered trials, totaling 5 in number across all muscles and subjects with trial 1 representing all –5 steps to transition; trial 2 representing all –4 steps to transition; trial 3 representing all –3 steps to transition; trial 4 representing all –2 steps to transition; trial 5 representing all –1 steps to transition. The ensembling for CSR differed slightly. The five strides extracted per speed interval trial were averaged to represent that interval trial for each muscle and subject. At this point in the processing, the ensembled envelopes were classified into four conditions or categories, running condition (RC); walking condition (WC); run to walk condition (RW); and walk to run condition (WR).

**Identifying the Change of Coordination**

Two methods served to distinguish the changing muscular coordination and from which statistical comparisons were conducted between the conditions.
Coefficient of Cross-Correlation, $R_{xy}$ (Li & Caldwell, 1999)

Determined the similarity of the activity periods (trials) within and across the conditions; as well as detected shifting of the same activation period and discriminated the significance of the shift. Within the five trials of the conditions, four comparisons were conducted, which are further explained in Table 2.5. Within the progression conditions, the trial of which all comparisons were based was the furthest step from the transition (Step –5). For WC, the slowest trial (-0.6 mph) and, for RC, the fastest trial (+0.6 mph) were selected as the standard pattern for comparison to ensure that the standard pattern was the best representative of the respective gait. Since the direction of the change in speed differed between the two progressions, the gaits were separated and processed independently, RW with RC and WR with WC.

Table 2.5: Cross-Correlation Analyses Order.

<table>
<thead>
<tr>
<th>COMPARISONS FOR RC AND RW</th>
<th>COMPARISONS FOR WC AND WR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 = FASTEST TRIAL/STEP-5</td>
<td>1 = SLOWEST TRIAL/STEP-5</td>
</tr>
<tr>
<td>TO FAST/STEP-4</td>
<td>TO SLOW/STEP-4</td>
</tr>
<tr>
<td>2 = FASTEST TRIAL/STEP-5</td>
<td>2 = SLOWEST TRIAL/STEP-5</td>
</tr>
<tr>
<td>TO MTS/STEP-3</td>
<td>TO MTS/STEP-3</td>
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<tr>
<td>3 = FASTEST TRIAL/STEP-5</td>
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</tr>
<tr>
<td>4 = FASTEST TRIAL/STEP-5</td>
<td>4 = SLOWEST TRIAL/STEP-5</td>
</tr>
<tr>
<td>TO SLOWEST/STEP-1</td>
<td>TO FASTEST/STEP-1</td>
</tr>
</tbody>
</table>

The table lists the correlation comparisons investigated for the conditions. The constant velocity conditions for walking and running are RC and WC. RW represents the decreasing velocity running condition leading to a run-to-walk transition. WR represents the increasing velocity walking condition leading to a walk-to-run transition. The running conditions were processed independently of the walking conditions since the step furthest from the gait transition in RW and WR was taken at different changes in velocity, decreasing velocities for RW and increasing velocities for WR.
The original $R_{xy}$ value ($R_0$) for each comparison was recorded along with the maximum $R_{xy}$ value ($R_i$) generated from shifting or translating the patterns amongst the standard pattern. Shifting was conducted in an attempt to produce a higher correlation between the patterns compared to demonstrate coordination timing changes. The difference of the values ($R_{\text{diff}}$) was calculated and recorded along with the shift value (Per) which was purported as a percentage of the stride cycle. Before any analyses of variance were conducted, the coefficients were transferred using a natural logarithmic to achieve a more normal distribution.

$$T_{0,i} = \frac{\ln(1 - R_{0,i})}{1 + R_{0,i}}$$

Where $T_{0,i}$ is the transferred value of $R_0$ or $R_i$; $\ln$ is the natural log; $R_{0,i}$ is the coefficient of cross-correlation with/without shifting.

Normality tests provided support that the transfer was successful and are displayed in Figure 2.9.
Figure 2.9: Normality Graphs. To test the assumption of normally distributed data for analyses of variance measures, a normality distribution test was conducted on the cross-correlation coefficients (R-values) whose distribution (red curve) is depicted in the first histogram. The Wilk-Shapiro value for the coefficients was good but a more normal distribution and thus a higher Wilk-Shapiro value was obtained by transferring the coefficients using a natural logarithmic. The second histogram depicts the distribution (red curve) of the transferred coefficients (Transferred R-Values).
Specific to each muscle investigated, a 3x4 factorial ANOVA (alpha level = .05) with repeated measures tested these variables for significant differences between the four comparisons, between the two conditions, and between the participants as well as tested for any significant interactions between the conditions and comparisons. Trend analyses followed the findings of the ANOVA. Detection of new activation periods or detection of disappearing periods was not applicable with the cross-correlation method. Therefore, the second method was required.

**Discrete Variables of Muscle Activation**

This particular method involved more subjective procedures to obtain the coordination changes, but did take into account the appearance and disappearance of muscle activation (periods). Criterion reference lines, based on percents (usually 10%) of the maximum envelope data point were superimposed over the linear envelopes. Figure 2.10 illustrates a criterion line found for one of the muscle linear envelopes. All points above this reference line represented when the muscle was activated, and all points below the reference line referred to when the muscle was at rest. The points that intersect the reference line corresponded to the moment of activation or deactivation (onset and offset) and determined the periods of activation and deactivation (duration). The overall peak magnitude value across the trials for each muscle and subject was recorded and utilized to find the relative peak magnitude (PeakM) of all activity periods which was purported as a percentage. Lastly, the times or the percentages of the stride cycle where the PeakM appeared were recorded (PeakT).
Figure 2.10: Graph of the Discrete Parameters. Depicts the ensemble curve for the vastus lateralis (VL) of subject 4 during the second walking trial at constant velocity (W2). The data points for the VL ensemble (blue line) were processed to find their maximum value. From the max, an activation threshold line at ten percent of the max (red line) was calculated. All points above this reference line occurred while the muscle was activated, and all points below the reference line occurred while the muscle was at rest. The points that intersect the reference line represent the moment of activation or deactivation (Onset and Offset) and determined the time of activation for the periods (Duration). VL displayed two periods of activation which are labeled in the graph (Period 1 and Period 2). The overall peak magnitude value across the trials was used to find the relative peak magnitude (PeakM) of all activity periods. The time of the stride cycle where the PeakM was observed were recorded (PeakT).
Statistical analyses across all conditions were practical for the discrete variables but required rearrangement of the trials by speed. Table 2.6 presents the new order of the trials.

Table 2.6: Discrete Analyses Order.

<table>
<thead>
<tr>
<th>RW</th>
<th>TRIAL 1 = - 1 STEP</th>
<th>Slowest</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRIAL 2 = - 2 STEP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRIAL 3 = - 3 STEP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRIAL 4 = - 4 STEP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRIAL 5 = - 5 STEP</td>
<td>Fastest</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WR</th>
<th>TRIAL 1 = - 5 STEP</th>
<th>Slowest</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRIAL 2 = - 4 STEP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRIAL 3 = - 3 STEP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRIAL 4 = - 2 STEP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRIAL 5 = - 1 STEP</td>
<td>Fastest</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RC &amp; WC</th>
<th>TRIAL 1 = SLOWEST</th>
<th>Slowest</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRIAL 2 = SLOW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRIAL 3 = MTS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRIAL 4 = FAST</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRIAL 5 = FASTEST</td>
<td>Fastest</td>
<td></td>
</tr>
</tbody>
</table>

The trials by condition were organized to allow for statistical analyses of the discrete parameters for all conditions. The constant velocity conditions for walking and running are RC and WC. RW represents the decreasing velocity running condition leading to a run-to-walk transition. WR represents the increasing velocity walking condition leading to a walk-to-run transition. The progression condition trials were ordered to correspond with the constant speed conditions. Since the speed decreased in RW, the trial order for RW was reversed. The closest step to transition, hence the slowest step within the progression, was ordered first, while the furthest step from transition or the fastest step was ordered last. In WR, speed increased therefore each step taken was at a faster speed, the step furthest from transition was the slowest, and the speed range paralleled RC and WC.
Onset, offset, duration, PeakM, and PeakT were tested for significance through analyses of variance (3x5 factorial ANOVA with repeated measures) at an alpha level of 0.05 for each activation burst of each muscle. The interaction of the conditions and trials were also analyzed and trend analyses were conducted on the statistically significant interactions, which are discussed in the next section.
RESULTS

The results indicated differences in the testing conditions in which continuously changing speed conditions (RW and WR) when compared to the constant speed conditions (RC and WC) showed pattern and discrete differences. These findings are further discussed in this section.

Gluteus Maximus and Rectus Femoris

Anatomically, the gluteus maximus (GM) primarily functions as a mono-articulate hip extensor and the rectus femoris (RF) dually functions as a hip flexor and a knee extensor. Figure 3.1 and 3.2 display the ensemble curves of GM and RF patterns where the differences of the overall patterns and most of the discrete parameters can be observed. Two periods of activation were observed from both muscles within one gait cycle during all four different conditions (Figure 3.1 and 3.2).

GM Activity

The first activation period for GM started prior to heel contact within the last 10% of stride cycle and ended before 30% of the gait cycle which was mid-stance phase for the walking conditions and late stance for the running conditions. Higher peak magnitudes of this period were present in running than in walking. A second activation period started late in the walking stance phase close to 40% of the gait cycle, past toe off at 60%, and ended during swing phase at 70%-80%. For running, the second period was observed exclusively during swing phase from 45%-80% of the stride cycle. Therefore, the GM functions indicated by the activity patterns were not alike when comparing the walk and run conditions.
Figure 3.1: Muscle Activity Patterns of Gluteus Maximus. The top two graphs are the ensemble curves of the two walking conditions: walking with constant velocity (WC) and with increased velocity that leads to walk-to-run transition (WR). 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 speed (WC). The bottom two graphs are for the running conditions: running with constant velocity (RC) and with decreased velocity that leads 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 the trials were decreasing in speed for RW. The trial designations for RC are the same as WC such that trial 1 represents the slowest trial and the trials were increasing with speed.
Both walking conditions displayed similar activity changes across different speeds, and these changes were reflected by the apparent differences in the magnitude of the patterns (Figure 3.1). With speed increasing (from trial 2 toward trial 5), the activity patterns resembled the patterns of the first trial less and less ($R_0$: $F [3, 33] = 2.96, p < .046$) for both conditions (see Figure A.A.1 the trend of $R_0$ with speed). This decrease in correlation between the trials with increasing speed was similarly observed between the two conditions; therefore no significant interaction was detected. With the running conditions, the activity patterns varied across different speeds, and these variations were signaled by the noticeable magnitude differences (Figure 3.1). More specifically, GM activity patterns were similar in RC, but the correlation between the fastest run (trial 1) and others decreased in RW (see Figure A.A.2 for the detailed trend). Hence as speed decreased, the activity pattern of trial 1 more closely resembled the activity pattern of trial 5 for running at constant speeds (RC) then for progressing from a run to a walk (RW). The discrepancy between how the correlation changed between the trials and conditions was supported statistically with the presence of a significant trial-speed interaction for the coefficient of cross-correlation $R_0$ ($F [3, 33] = 6.06, p < .002$).

As speed increased, the peak magnitude (PeakM) of the activity period increased for all conditions, however the manner of the increase differed resulting in a significant condition/trial interaction ($F [12, 132] = 2.90, p < .001$). This interaction was demonstrated by several facts: the trend of PeakM for WC and RW increased linearly as speed increased; no trend of PeakM for RC with speed was detected; the trend of PeakM for WR increased quadratically which indicates the preparation for gait. Transitions induced more changes than to adjust to the speed (Figure A.A.3). The time to PeakM (PeakT) of the first activation period was also of note since it
appeared approximately 5% later in running than in walking (Figure 3.1; $F_{[3, 33]} = 3.62, p < .023$). Increasing the speed changed the duration, offset, and peak magnitude of the second activation period (trial effects--dur: $F_{[4, 32]} = 6.34, p < .001$; offset: $F_{[4, 32]} = 3.59, p < .016$; PeakM: $F_{[4, 32]} = 9.06, p < .000$) for all four conditions.

Table 3.1: Gluteus Maximus ANOVA’s Summary.

<table>
<thead>
<tr>
<th>Patterns</th>
<th>Variables</th>
<th>Effects and Interactions</th>
<th>Degrees of Freedom</th>
<th>$F$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>R0</td>
<td>Cond*Trial</td>
<td>3, 33</td>
<td>6.06</td>
<td>0.002</td>
</tr>
<tr>
<td>W</td>
<td>R0</td>
<td>Trial</td>
<td>3,33</td>
<td>2.96</td>
<td>0.046</td>
</tr>
<tr>
<td>Period 1</td>
<td>PeakM</td>
<td>Cond*Trial</td>
<td>12, 132</td>
<td>2.90</td>
<td>0.001</td>
</tr>
<tr>
<td>Period 1</td>
<td>PeakT</td>
<td>Cond</td>
<td>3, 33</td>
<td>3.62</td>
<td>0.023</td>
</tr>
<tr>
<td>Period 2</td>
<td>Dur</td>
<td>Trial</td>
<td>4, 32</td>
<td>6.34</td>
<td>0.001</td>
</tr>
<tr>
<td>Period 2</td>
<td>Offset</td>
<td>Trial</td>
<td>4, 32</td>
<td>3.59</td>
<td>0.016</td>
</tr>
<tr>
<td>Period 2</td>
<td>PeakM</td>
<td>Trial</td>
<td>4, 32</td>
<td>9.06</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

The correlation and discrete parameters of the gluteus maximus activity patterns are summarized in the table above. For the correlation analyses, the first column refers to the gait pattern investigated. The running conditions (R) are running at constant velocity (RC and running at decreasing velocity leading to a run-to-walk transition (RW). The walking conditions (W) are walking at constant velocity (WC) and walking at increasing velocity leading to a walk-to-run transition (WR). For the discrete analyses, the first column refers to the activation period investigated: Period 1 = first activation period; Period 2 = second activation period. The remaining columns report the effect or interaction investigated, the degrees of freedom for the variable and for the error term used, the F-value calculated, and the p-value determined for the parameters, which are listed in the second column. Data of all subjects (N = 12) were included in the correlation analysis and Period 1 of the discrete analyses. Data of only nine subjects (N = 9) were included for Period 2 of the discrete analyses since two activity periods were not presented for the rest of the three subjects.
RF Activity

Similar to GM, the first activation period of the RF started just prior to heel contact near the last 15% of the cycle for running and the last 10% for walking. This period ended before 25% of the gait cycle, which consisted of half of the walking stance phase and most of the running stance phase. A second activation period produced separate observations between the conditions as well. For the two walking conditions, the second period bridged over the two stride phases, beginning during mid-stance at approximately 30-40% of the stride cycle and ending at early (70%) to mid-swing (80%). In running, the second period began after toe off during swing at 45% of the stride cycle for RC and at 35% of the stride cycle for RW. This period ended around late swing at 75% of the stride cycle for RC and at 70% of the stride cycle for RW.

The RF’s activity patterns during walking (WC and WR) underwent activity pattern changes (Figure 3.2) across trials in which the magnitude of the activity patterns changed with the increasing speed (R₀: F [3, 33] = 14.60, p < .0001). With increasing speed, the activity patterns less resembled the patterns of the slowest trial (trial 1), which was reflected by the decrease of the cross correlation coefficients (Figure A.A.4). The running conditions underwent less distinct activity pattern changes than the walking conditions (Figure 3.2). Nonetheless, as speed decreased, the activity patterns changed (indicated by decreased R₀: F [3, 33] = 3.02, p < .044, see Figure A.A.5 for details).
Figure 3.2: Muscle Activity Patterns of Rectus Femoris. The top two graphs are the ensemble curves of the two walking conditions: walking with constant velocity (WC) and with increased velocity that leads to walk-to-run transition (WR). 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 speed (WC). The bottom two graphs are for the running conditions: running with constant velocity (RC) and with decreased velocity that leads 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 the trials were decreasing in speed for RW. The trial designations for RC are the same as WC such that trial 1 represents the slowest trial and the trials were increasing with speed.
The correlation and discrete parameters of the rectus femoris activity patterns are summarized in the table above. For the correlation analyses, the first column refers to the gait pattern investigated. The running conditions (R) are running at constant velocity (RC) and running at decreasing velocity leading to a run-to-walk transition (RW). The walking conditions (W) are walking at constant velocity (WC) and walking at increasing velocity leading to a walk-to-run transition (WR). For the discrete analyses, the first column refers to the activation period investigated: Period 1 = first activation period; Period 2 = second activation period. The remaining columns report the effect or interaction investigated, the degrees of freedom for the variable and for the error term used, the F-value calculated, and the p-value determined for the parameters, which are listed in the second column. Data of all subjects (N = 12) were included in the correlation analysis and Period 1 of the discrete analyses. Data of only nine subjects (N = 9) were included for Period 2 of the discrete analyses since two activity periods were not presented for the rest of the three subjects.

The discrete parameters more closely revealed the activity pattern changes. PeakM of the first period increased with speed although the manner of increase differed across the conditions (a significant condition/trial interaction was observed for PeakM, $F_{[12, 132]} = 6.83, p < .0001$).

Peak magnitude increased in a linear fashion for WC and in a quadratic fashion for WR as the speed effect was amplified by the preparation for gait transition (Figure A.A.6). The duration of the period for the two running conditions underwent changes (Figure 3.2) as a result of decreased speed in which these changes were not similar across the conditions (interaction: $F_{[12, 132]} =1.92, p < .038$). Further analyses revealed that duration increased with speed linearly for WR and RC and decreased linearly with speed in the RW condition (Figure A.A.7). No significant
trends were observed in WC. Magnitude changes were also evident in the second activation period (Figure 3.2). Overall, the PeakM of the constant speed conditions was greater than the conditions featuring the gait transitions and PeakM was greater at higher speeds, in which a significant interaction was detected ($F_{[12, 90]} = 3.95, p < .0001$). PeakM increased linearly as with increasing speed for all conditions, except RC in which no trend was observed (Figure A.A.8). Increasing the speed also produced observable increases in the duration of the second period (Figure 3.2, trial effects--$F_{[4, 32]} = 4.27, p < .007$).

Vastus Lateralis and Biceps Femoris

Vastus lateralis (VL) represented the monoarticulate knee extensors anatomically in this study, while the biceps femoris (BF) represented the bi-articulate hip extensors and knee flexors. The overall pattern differences and discrete differences can be observed in Figure 3.3 and 3.4. These figures are comprised of the ensemble curves of the VL and BF activity patterns. The figures display two periods of activation for both muscles within one gait cycle during all of the conditions.

**VL Activity**

The first activation period for VL began just prior to heel contact during the last 10% of the cycle and ended before 35% of the stride cycle. For walking, this period continued into mid-stance: 25% for WC and 30-40% for WR. For running, the period ended right at or past toe-off: 30% for RC and 35% for RW. A second activation period started at before 55% of the cycle and ended around 70-75% of the stride cycle. Relative to the stride phases, the walking second period began during late stance for WC and during toe-off for WR and disappeared after toe off during early swing. The second activation period observed in running appeared after toe off and disappeared during mid-swing.
As seen in Figure 3.3, both walking conditions exhibited similar activity pattern changes as speed increased. The pattern magnitude increased in a similar fashion for both conditions (from slow to fast walking) resulting in decreasing correlation between the patterns of different steps (Figure A.A.9; $R_0: F[3, 33] = 9.01, p < .0001$). For running, the activity patterns displayed changes with the decreased speed but also differences between the two conditions (interaction: $R_0: F[3, 33] = 4.77, p < .007$). As seen in Figure 3.3, the changes in the RC activity patterns which were primarily related to pattern magnitude were less distinct than the changes in RW which appeared to result from magnitude and morphological changes (Figure A.A.10).

### Table 3.3: Vastus Lateralis ANOVA’s Summary.

<table>
<thead>
<tr>
<th>Patterns</th>
<th>Variables</th>
<th>Effects and Interactions</th>
<th>Degrees of Freedom</th>
<th>$F$</th>
<th>$p$</th>
</tr>
</thead>
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<td>Trial</td>
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<td>Cond*Trial</td>
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</table>

The correlation and discrete parameters of the vastus lateralis activity patterns are summarized in the table above. For the correlation analyses, the first column refers to the gait pattern investigated. The running conditions (R) are running at constant velocity (RC) and running at decreasing velocity leading to a run-to-walk transition (RW). The walking conditions (W) are walking at constant velocity (WC) and walking at increasing velocity leading to a walk-to-run transition (WR). For the discrete analyses, the first column refers to the activation period investigated: Period 1 = first activation period; Period 2 = second activation period. The remaining columns report the effect or interaction investigated, the degrees of freedom for the variable and for the error term used, the $F$-value calculated, and the $p$-value determined for the parameters, which are listed in the second column. Data of all subjects ($N = 12$) were included in the correlation analysis and Period 1 of the discrete analyses. Data of only three subjects ($N = 3$) were included for Period 2 of the discrete analyses since two activity periods were not presented for the rest of the nine subjects.
Figure 3.3: Muscle Activity Patterns of Vastus Lateralis. The top two graphs are the ensemble curves of the two walking conditions: walking with constant velocity (WC) and with increased velocity that leads to walk-to-run transition (WR). 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 speed (WC). The bottom two graphs are for the running conditions: running with constant velocity (RC) and with decreased velocity that leads 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 the trials were decreasing in speed for RW. The trial designations for RC are the same as WC such that trial 1 represents the slowest trial and the trials were increasing with speed.
The discrete parameters examined also presented activity pattern changes. For the activity period when the speed was increased, PeakM for all conditions increased linearly (Figure A.A.11). However, the magnitude of increase differed between the conditions and RC had no discernable trend resulting in a condition/trial interaction ($F_{[12, 132]} = 6.17, p < .0001$). Offset of the period was also affected by the increased speed (trial: $F_{[4, 44]} = 3.01, p < .028$) and by the different conditions (cond: $F_{[3, 33]} = 4.12, p < .014$), which was best observed when comparing the constant speed conditions (WC and RC) to the variable speed conditions (WR and RW). The PeakM for the second activity period also changed with the increased speed and changed differently between the conditions ($F_{[12, 19]} = 2.31, p < .050$). The manner of PeakM change, which was predominately an increase in magnitude, differed as well (Figure 3.3). Trend analyses further revealed the manner of change: linear increase for WR, quadratic increase for WC, and no discernable trends for RC and RW (Figure A.A.12).

**BF Activity**

The first activation period of BF occurs during swing. In walking, the period began during the last 20% of stride, continued through heel contact, and ended in early stance at 20%-30% of stride. The first activity period for running started in the last 30% of the cycle; remained active past heel contact, throughout stance phase, and past toe off; ended at early swing around 40% of the cycle. A second activity period was observed in walking and running; however this period’s presence was more distinct in running than in walking. For walking, the period started just prior to toe off at 50%-60 of stride and ended early in swing at 70% of the stride cycle. The second activity period for running appeared after toe off at 45% of the cycle and ended later in the swing phase at 70% of the cycle.
As pictured in Figure 3.4, the walking activity patterns of both conditions were affected by the increase in speed ($R_0$: $F [3, 33] = 12.02, p < .0001) similarly. The activity pattern changes were primarily marked by an increasing pattern magnitude. As the amplitude increased and other changes influenced the pattern, the correlation between the pattern of the slowest walking trial and each sequential trial decreased (See Figure A.A.13). The manner of the changes was consistent between the two walking conditions, which was not the observation for the running conditions. As the speed decreased in RC, the activity pattern’s magnitude increased instead of decreasing, which was observed in RW. Hence, not only were the activity patterns influenced by the decreased speed but they also reacted differently to the conditions ($R_0$: $F [3, 33] = 8.58, p < .0001; $ Figure A.A.14).

<table>
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The correlation and discrete parameters of the biceps femoris activity patterns are summarized in the table above. For the correlation analyses, the first column refers to the gait pattern investigated. The running conditions (R) are running at constant velocity (RC) and running at decreasing velocity leading to a run-to-walk transition (RW). The walking conditions (W) are walking at constant velocity (WC) and walking at increasing velocity leading to a walk-to-run transition (WR). For the discrete analyses, the first column refers to the activation period investigated: Period 1 = first activation period; Period 2 = second activation period. The remaining columns report the effect or interaction investigated, the degrees of freedom for the variable and for the error term used, the F-value calculated, and the p-value determined for the parameters, which are listed in the second column. Data of all subjects ($N = 12$) were included in the correlation analysis and Period 1 of the discrete analyses. Data of only three subjects ($N = 3$) were included for Period 2 of the discrete analyses since two activity periods were not presented for the rest of the nine subjects.
Figure 3.4: Muscle Activity Patterns of Biceps Femoris. The top two graphs are the ensemble curves of the two walking conditions: walking with constant velocity (WC) and with increased velocity that leads to walk-to-run transition (WR). 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 speed (WC). The bottom two graphs are for the running conditions: running with constant velocity (RC) and with decreased velocity that leads 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 the trials were decreasing in speed for RW. The trial designations for RC are the same as WC such that trial 1 represents the slowest trial and the trials were increasing with speed.
The discrete features of the BF activity patterns also displayed speed and condition influenced changes, although no interaction was detected. Increasing the speed resulted in a longer duration \((F[4, 44] = 4.44, p < .004)\). Generally, the speed increase also resulted in a greater PeakM \((F[4, 44] = 12.57, p < .0001)\) for activity patterns of the first period with the exception of RC. Also, the amplitude of the first period activity patterns in WC and WR were not level. Hence, a condition effect was observed for PeakM \((F[3, 33] = 3.12, p < .039)\). For the second activation period, onset appeared earlier as speed increased \((F[4, 8] = 5.43, p < .021)\).

**Tibialis Anterior, Gastrocnemius, and Soleus**

From an anatomy perspective, the monoarticular ankle dorsiflexor was represented by the tibialis anterior (TA); the bi-articulate ankle plantar flexor and knee flexor was represented by the gastrocnemius (GAS); the monoarticular ankle plantar flexor was represented by the soleus (SOL). Figures 3.5, 3.6, and 3.7 illustrate the ensemble curves of the activity patterns for the TA, GAS, and SOL in order to better reference pattern differences and discrete activation period differences. Tibialis anterior exhibited either a single activation period or two periods dependent on the gait (Figure 3.5). GAS and SOL patterns consisted of only one activation period (Figure 3.6 and 3.7).

**TA Activity**

Theoretically, the role of this muscle differs between the two gaits; therefore the general observations of the TA muscle patterns are presented in detail according to condition. The pattern during WC displayed two activation periods. The activity of the first period began during the last 10% of the cycle and ended during mid-stance at 20%. The second period started just prior to toe off during late stance at 55% and ended during swing at approximately 75% of the
cycle. The WR patterns were less distinct as compared to the WC patterns. For the WR trials in which two activation periods were observed, the activity of the first period started during the same time of the cycle as in WC (-10% to 15%) but possessed less magnitude. For the second activation period, activity initiated and ended parallel to the WC second period (55%-75% of the cycle). For the WR trials which only displayed one activation period, activity started almost at half of the previous stride at -45% (55%) of the cycle and ended at 15% of the cycle. For the running conditions, only one activation period was clearly discerned which started at during the previous stride’s swing at -55% (45%) of the cycle and ended at toe off or just prior at approximately 30% of the cycle.

The changing presence of a second activation period along with the overall activity pattern’s response to increasing speed conditions resulted in the patterns of each walking trial relating less to the patterns of the slowest trial (R₀ trial effect: $F [3, 33] = 9.45, p < .0001$, Figure A.A.15). The preparation for gait transition present in WR induced changes, which resulted in less correlation, however the effects were different than from WC (R₀ condition effect: $F [1, 11] = 7.42, p < .020$, Figure A.A.15). Despite the presence of effects from increasing speed and from inducing transition, no interaction was observed in walking. Yet when the speed was decreased and when comparing the presence or lack of presence of gait transition, a running interaction was evident (R₀: $F [3, 33] = 11.73, p < .0001$). Without the preparation for a run-to-walk transition (as in RC), the activity patterns between the trials remained similar. For RW, the correlation of the patterns between the fastest running trial and the others decreased slightly (See Figure A.A.16 for the correlation trends).
Figure 3.5: Muscle Activity Patterns of Tibialis Anterior. The top two graphs are the ensemble curves of the two walking conditions: walking with constant velocity (WC) and with increased velocity that leads to walk-to-run transition (WR). 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 speed (WC). The bottom two graphs are for the running conditions: running with constant velocity (RC) and with decreased velocity that leads 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 the trials were decreasing in speed for RW. The trial designations for RC are the same as WC such that trial 1 represents the slowest trial and the trials were increasing with speed.
Table 3.5: Tibialis Anterior ANOVA’s Summary.

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The correlation and discrete parameters of the tibialis anterior activity patterns are summarized in the table above. For the correlation analyses, the first column refers to the gait pattern investigated. The running conditions (R) are running at constant velocity (RC) and running at decreasing velocity leading to a run-to-walk transition (RW). The walking conditions (W) are walking at constant velocity (WC) and walking at increasing velocity leading to a walk-to-run transition (WR). For the discrete analyses, the first column refers to the activation period investigated: Period 1 = the activation period. The remaining columns report the effect or interaction investigated, the degrees of freedom for the variable and for the error term used, the F-value calculated, and the p-value determined for the parameters, which are listed in the second column. Data of all subjects (N = 12) were included in the correlation analysis and Period 1 of the discrete analyses.
Only the discrete features of TA’s first activation period were examined since the second activation period was not always present. The first activation period responded to the increase in speed by changing the PeakM ($F_{12, 132} = 5.48, p < .0001$) and duration ($F_{12, 132} = 2.58, p < .004$) of the period differently for the conditions. For PeakM, the walking conditions presented an amplitude difference between the activity patterns of WC and WR and a linear increase in magnitude as speed increased for both (Figure 3.5). Also less discernable magnitude changes were evident in the running conditions (See Figure A.A.17 for trend analyses). As the speed increased which caused the second activation period to diminish, the first activity period grew linearly in duration (Figure 3.5 and Figure A.A.18). The change in activity duration was also evident through changes in onset and offset. The increase in speed along with the conditions influenced onset but not with an interaction (condition effects: $F_{3, 33} = 7.30, p < .001$ and trial effects: $F_{4, 44} = 19.75, p < .0001$). Offset of activity patterns of the of the first period also changed from condition to condition which was mostly induced through the change in activity between the first and second periods of TA and induced by gait ($F_{3, 33} = 6.45, p < .002$; Figure 3.5).

**GAS Activity**

As stated earlier and seen in Figure 3.6, GAS patterns featured only one activation period, which observably changed across trials and conditions. For walking (WC and WR), the period began at mid-stance around 25% of the cycle and ended prior to toe off at 50%. The pattern during the running conditions started during the last 10% of the cycle, continued past heel contact and toe off, and ended during swing at 50% of the cycle. Hence, the GAS activity began earlier and had more activity during swing in running than in walking.
Figure 3.6: Muscle Activity Patterns of Gastrocnemius. The top two graphs are the ensemble curves of the two walking conditions: walking with constant velocity (WC) and with increased velocity that leads to walk-to-run transition (WR). 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 speed (WC). The bottom two graphs are for the running conditions: running with constant velocity (RC) and with decreased velocity that leads 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 the trials were decreasing in speed for RW. The trial designations for RC are the same as WC such that trial 1 represents the slowest trial and the trials were increasing with speed.
Observing just the walking patterns revealed activity pattern changes induced by the increasing speed (R₀: $F[3, 33] = 7.92, p < .0001$). These changes, which appeared to be related to pattern magnitude changes, resulted in decreasing correlation between the pattern of the slowest trial and the patterns of the subsequent trials (See Figure A.A.19). The running activity patterns also changed with speed, but the preparation of a run-to-walk transition also affected the patterns as evident in a condition/trial interaction (R₀: $F[3, 33] = 11.42, p < .0001$). High correlation was observed in the RC comparisons which remained consistent as speed decreased and was decreasing in the RW comparisons as speed decreased (See Figure A.A.20).

Table 3.6: Gastrocnemius ANOVA’s Summary.

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<th>Patterns</th>
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<th>p</th>
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The correlation and discrete parameters of the gastrocnemius activity patterns are summarized in the table above. For the correlation analyses, the first column refers to the gait pattern investigated. The running conditions (R) are running at constant velocity (RC) and running at decreasing velocity leading to a run-to-walk transition (RW). The walking conditions (W) are walking at constant velocity (WC) and walking at increasing velocity leading to a walk-to-run transition (WR). For the discrete analyses, the first column refers to the activation period investigated: Period 1 = the activation period. The remaining columns report the effect or interaction investigated, the degrees of freedom for the variable and for the error term used, the F-value calculated, and the p-value determined for the parameters, which are listed in the second column. Data of all subjects (N = 12) were included in the correlation analysis and Period 1 of the discrete analyses.
The shift and other morphological pattern changes in activation were also evident by the discrete parameters of the GAS. PeakM increased across the conditions as speed increased. However the manner of increase included both linear trends and quadratic trends (condition/trial interaction: $F_{[12, 132]} = 16.72, p < .0001$). All running conditions (RC and RW) displayed a linear increase along with the constant speed condition of walking (WC); WR exhibited the quadratic trend (Figure A.A.21). Duration also changed with the increasing speed across the conditions (condition/trial interaction: $F_{[12, 132]} = 3.27, p < .0001$). Each walking activation period remained active longer; this increase in duration was linear for WC and WR. For RW, the duration decreased in a quadratic fashion. RC exhibited neither trend upon analyses (See Figure A.A.22 for trends). The lengthening of the activation period resulted from the progressively later offset of the activity as speed increased (condition/trial interaction: $F_{[12, 132]} = 3.51, p < .0001$). The offset of the period changed in a linear fashion for the running conditions and for WR. WC displayed no discernable trend (See Figure A.A.23 for trends). Duration was also affected by the onset of the period. Regardless of a significant onset interaction, changes in the GAS pattern were present across the conditions ($F_{[3, 33]} = 15.34, p < .0001$) and as speed increased ($F_{[4, 44]} = 7.69, p < .0001$). When comparing the activity patterns of walking and running, the timing of the activation peak changed, becoming an earlier event in running than in walking (PeakT: $F_{[3, 33]} = 52.50, p < .005$).
SOL Activity

The appearance of the SOL activity period distinctively varied across the two gaits. The period began during the last 10% of the cycle, continued past heel contact, and ended around 50-60% of the cycle which constituted toe off for the walking conditions and swing phase for the running conditions.

The activity patterns for walking exhibited changes in timing as well as magnitude as speed increased (R₀: $F[3, 33] = 18.47, p < .0001$; $R_{\text{max}}$: $F[3, 33] = 15.11, p < .0001$). More specifically, a walking related phase shift was evident for SOL as speed increased, such that the correlation of the comparisons without the consideration of shifting $R_{\text{diff}}$ differed from the maximum correlation of the comparisons which included shifting $R_{\text{max}}$ ($R_{\text{diff}}$: $F[3, 33] = 4.98$, $p < .006$; See figures A.A.24 and A.A.25 for differences between $R_{\text{diff}}$ and $R_{\text{max}}$), and the amount of shifting required to obtain the maximum correlation between the activity patterns of the slowest trial and the activity patterns of the subsequent trials increased as speed increased (Per: $F[3, 33] = 5.66$, $p < .003$; Figure A.A.26). The running activity patterns changed as speed decreased and as a result of the preparation of run-to-walk transition present in RW (condition/trial interaction: $R_{\text{diff}}$: $F[3, 33] = 14.58$, $p < .0001$ and $R_{\text{max}}$: $F[3, 33] = 15.79$, $p < .0001$). Even though the activity patterns were shifting to an earlier point in the cycle for RC and to a later point for RW, only the effect of speed was significant ($F[3, 33] = 3.07$, $p < .041$) and similar changes in correlation were observed between $R_{\text{diff}}$ and $R_{\text{max}}$ (See Figures A.A.27 and A.A. 28 for $R_{\text{diff}}$ and $R_{\text{max}}$ and Figure A.A.29 for the phase shift).
Figure 3.7: Muscle Activity Patterns of Soleus. The top two graphs are the ensemble curves of the two walking conditions: walking with constant velocity (WC) and with increased velocity that leads to walk-to-run transition (WR). 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 speed (WC). The bottom two graphs are for the running conditions: running with constant velocity (RC) and with decreased velocity that leads 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 the trials were decreasing in speed for RW. The trial designations for RC are the same as WC such that trial 1 represents the slowest trial and the trials were increasing with speed.
Similar to the GAS, the shift and other morphological pattern changes in activation were also evident by the discrete parameters of the SOL. PeakM increased through different means across the conditions as speed increased (condition/trial interaction: $F_{[12, 132]} = 11.55, p < .0001$). All running conditions (RC and RW) displayed a linear increase along with the constant speed condition of walking (WC); WR exhibited the quadratic trend (Figure A.A.30). Duration changed with the increasing speed across the conditions (condition/trial interaction: $F_{[12, 132]} = 5.02, p < .0001$). For walking, each activation period remained active longer, with the change in duration displaying a linear trend (See Figure A.A.31). For running, the duration linearly decreased as speed increased (Figure A.A.31). The offset event of the period also changed with the increase in speed and with the different gaits ($F_{[12, 132]} = 2.67, p < .003$). Offset linearly shifted later in the period for walking and earlier in the period for running (Figure A.A.32). Onset also changed with the increasing speed ($F_{[4, 44]} = 6.02, p < .001$) and with the conditions ($F_{[3, 33]} = 4.02, p < .015$). The timing of the activation peak changed with gait ($F_{[3, 33]} = 57.59, p < .0001$) and with the increase of speed ($F_{[4, 44]} = 4.02, p < .007$).
The correlation and discrete parameters of the soleus activity patterns are summarized in the table above. For the correlation analyses, the first column refers to the gait pattern investigated. The running conditions (R) are running at constant velocity (RC) and running at decreasing velocity leading to a run-to-walk transition (RW). The walking conditions (W) are walking at constant velocity (WC) and walking at increasing velocity leading to a walk-to-run transition (WR). For the discrete analyses, the first column refers to the activation period investigated: Period 1 = the activation period. The remaining columns report the effect or interaction investigated, the degrees of freedom for the variable and for the error term used, the F-value calculated, and the p-value determined for the parameters, which are listed in the second column. Data of all subjects (N = 12) were included in the correlation analysis and Period 1 of the discrete analyses.

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<td>4.02</td>
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DISCUSSION

General muscle activity patterns were similar to the previous literature for both gaits. In particular, the activity coordination between the agonist and antagonists and between the more distal muscles resembled previous reports. However, the main focus of this study was to further quantify and investigate the muscle coordination behavior during progression, which had previously only been investigated by two studies (Nilsson et al., 1985; Prilutsky & Gregor, 2001). Based on the coordination observations of those studies in addition to the kinetic observations of Li and Hamill (2001), the following predictions were made: if nonlinear coordination behavior exists as locomotion nears transition, then significant differences between stable locomotion and transition locomotion should be observed and these differences are better represented within a varying velocity condition than a differing constant velocity condition.

The results indicated differences in the testing conditions in which the constant speed conditions (RC and WC) produced similar results to previous gait transition studies (Nilsson et al., 1985; Prilutsky & Gregor, 2001), and as such supported the presence of coordination differences between stable locomotion and transition locomotion. Yet, different activity patterns and coordination changes were exhibited in the continuously changing speed conditions (RW and WR) when compared to the constant speed conditions (RC and WC).

For the constant velocity conditions, running activity patterns were more resistant to overall pattern changes as induced by speed than walking since more activity pattern differentiation, as marked by decreasing correlation, was observed during walking than during running. Phase shifting of the activity patterns was not the primary coordination change utilized by the muscles in either gait or in speed condition, with the exception of the more distal muscles (muscles surrounding the ankle joint) whose shifts were related to conditions. Increases in activity pattern magnitude and duration were much more prevalent.
Constant Velocity and Muscle Activity Between Running and Walking

Previous literature provided descriptions for muscle activities during walking and running; however, only few have reported muscle activities related to gait transition speeds. Reviewed in this paper were two studies (Nilsson et al., 1985; Prilutsky & Gregor, 2001) upon which the observations of the constant velocity conditions in general support. Due to the experimental design of the previous studies, only the results concerning the constant velocity conditions for the gaits are discussed here. Differences between the two gaits when conducted at greater or less preferred speeds were evident in all the muscles through overall activity pattern changes and discrete activity changes.

The activity patterns remained highly correlated for running regardless of speed and for walking at slower speeds (gluteus maximus-GM, rectus femoris-RF, vastus lateralis-VL, biceps femoris-BF, tibialis anterior-TA). Exceptions were revealed when a phase shift for the activity patterns were observed, in which the phase shifting maintained high correlation for walking and running regardless of speed (gastrocnemius-GAS and soleus-SOL). For GAS and SOL, a shift in timing for the single activation period between the gaits was observed by all studies. According to Nilsson et al. (1985), the GAS activity period during walking, which began after heel contact, had reciprocal timing with TA’s period 1, but when running, the GAS and TA have some co-activation present since the GAS activity patterns shifted to an earlier onset during the stride cycle. The present study supported the presence of co-activation between the dorsiflexors (TA) and plantar flexors (GAS and SOL) during running with all three muscles represented.
demonstrating the co-presence of activation from at least the last 10% of cycle during swing to 40% of the stride cycle which incorporated stance and toe off. Further evidence of the gait-related shift was duration, offset, and onset changes between the conditions. However, the full scope of the changes significance cannot be fully discussed without consideration of the other conditions.

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 gaits (WC and RC), but the magnitude gains were disproportional such that the magnitude increases for running were less than the increases for walking (gluteus maximus-GM, rectus femoris-RF, vastus lateralis-VL, tibialis anterior-TA, gastrocnemius-GAS, and soleus-SOL). Prilutsky & Gregor (2001) and this study observed that at greater speeds the running activity magnitudes were less than the walking activity magnitudes. 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 (GAS and SOL). For RF, duration for period 1 linearly increased for RC while remaining consistent for WC. The longer activation of period 1 in RC and not in WC was possibly related to the speculated role of providing joint stability along with propelling the body during stance. For GM, Nilsson et al. (1985) reported significant changes as a result to increasing speed in which the onset of the stance activation period shifted to an earlier time in the cycle, which was not observed in this study. However, a second activation period (Period 2) was observed during
swing whose offset, duration, and magnitude were changing with the increased speed for both gaits. Since the activities observed by Nilsson et al. shifted to an earlier time (during swing before heel contact), it was likely that the beginning of this activity corresponded to period 2. The presence of period 2 during swing allows for speculation of a swing-related role for GM in addition to its support and propel role (period 1). Despite acknowledging the presence of two periods of the TA activation within one stride cycle, the previous transition studies (Nilsson et al., 1985; Prilutsky & Gregor, 2001) approached the activity patterns as if only one period was observed. In the case of this current study, the presence of the second period which was observed mostly in the constant velocity walking condition (WC) was not consistently observed in the progression conditions (WR and RW) or in the constant running velocity condition (RC). The disappearance of period 2 when transitioning to or from running (WR and RW) or when running itself (RC) further supported the speculated functional differences of the TA regarding the control of the ankle during the two gaits. The merging of period 2 into period 1 resulting in the shifting onset and the longer duration of period 1 corresponded to Nilsson et al. running specific observation of earlier shifting of the TA activity period within the gait cycle. For GAS and SOL, activation duration linearly increased in walking with the increasing speed but remained active for less time than during running, whose duration remained consistent regardless of speed. The walking offset shifted to a later time in the cycle.
Progressing toward transition versus locomoting at different constant velocities

Prilutsky and Gregor (2001) speculated that switching from walking to running would reduce the peak magnitude of the muscular activities at greater walking speeds or as the speed advanced beyond the preferred transition speed. Also, switching from running to walking would reduce the peak magnitude of the muscular activities 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 or where they compared to the constant velocity observations. When observing the muscles’ activity pattern changes of the preparation period marked by the five preceding steps to transition for both progressions, differences between the overall activity patterns of the conditions were present and the degree to which the peak magnitude changed was not as distinct as the constant velocities. Furthermore, the manner of change for the magnitudes and durations of the activities had quadratic trends or different linear trends than the constant velocities. In general, those changes were magnified as the steps were closer to the gait transition.

The overall muscle patterns distinguished the running more than the walking conditions. Progressing from running to walking (RW) less resembled running at different velocities (RC) for all muscles as seen in condition/trial interactions for the correlation (GM, RF, VL, BF, TA, GAS, and SOL). The walk-to-run progression (WR) in comparison with walking at different constant velocities (WC) behaved similarly as no correlation interaction or condition effect was observed for all muscles with the exception of TA. The TA activity patterns at faster constant
velocities lost their resemblance to the patterns at slower constant velocities. However, the
decrease in resemblance between WC and WR was not the same such that the decrease in WR
was more distinct. Observations based on the ensemble curves of the muscles (VL and BF) and
the discrete parameters further support the presence of different coordination strategies between
progression (RW and WR) and maintaining the gait beyond preferred 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 BF 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 (2001) and observed in the RC condition was not
observed in RW. These observations 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 velocities such
that a trend was detected for the progressions but not for the constant velocities (GM, RF, VL,
GAS); that when progressions and constant velocities revealed linear trends, those trends were at
different slopes (RF, VL, TA, GAS, SOL); that a quadratic trend was detected for the
progressions but not the constant velocities (GM, RF, GAS, SOL). When only the progression
trend was determined, linear increases in the magnitude of GM, RF, and VL for run-to-walk;
linear increase in the duration of RF for walk-to-run; and quadratic decrease in the duration of GAS for run-to-walk were observed. Even though the magnitude trends for VL and the magnitude and duration trends for TA during WR and WC were linear, the magnitude at WR was initially smaller than at WC and as the speed increased the magnitude for the walk-to-run progression increased at a greater gain than WC. For GAS and SOL, the activation duration during WR was consistently greater than the activation duration during WC. In terms of differences in the linear trends revealed for magnitude during running, the magnitude for RC was consistently greater than RW for GAS and SOL. Activation duration for running revealed the following differing linear aspects: RC duration increased and RW duration decreased (RF); both running conditions showed increasing duration but RW was consistently greater than RC (TA); both running conditions showed decreasing duration but RW was consistently greater than RC (SOL). 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, GAS, and SOL. The GAS activation duration for RW initially decreased, but as transition neared, during the last two steps, the duration remained at the same length. Regardless of how the magnitude and duration changed, they exhibited transitional behavior.
Muscular Coordination with Constant Velocity and with Varying Velocity

Although there were different responses in the muscle coordination to the application of velocity and to the type of gait or progression, patterns to these responses emerged. Most noticeable was the presence of increasing coordination changes in the more distal the muscles became. The muscles articulating the ankle experienced phase shifting, morphological changes, magnitude increases, duration changes, and offset shifting. The TA experienced the disappearance of an activation period comparing running activation patterns to walking activation patterns, and the GAS and SOL experienced phase shifting from mid-stance activation in walking to prior heel contact activation in running. At no other joint was there such a distinction in coordination. The antagonist muscle patterns changed from displaying reciprocal activation patterns to more co-activation patterns. As locomotion progressed to running or during running, the antagonist pair displayed longer co-activation. The co-contraction between TA and GAS/SOL best represent this phenomenon, but it can also be observed between RF/VL and BF activity patterns, particularly with the co-activation during running heel contact and stance. Nonlinear trends were most prevalent in the progressions. More specifically the WR progression demonstrated non-linear increases in pattern magnitude for all muscles (except BF) with the increasing changes witnessed as close to the transition. Nonlinear trends were also noticed in activity duration during the RW progression.
Limitations and Future Directions

The ability of the treadmill used to accelerate and decelerate the treadmill belt directly and indirectly affected the study. Since the acceleration could not be changed the study was limited to investigating only the steps which demonstrated velocity changes, which were the five preceding steps to transition and not any steps after transition for both gait transitions. Although the preparation to transition was studied with no related problems, the recovery after transition could not be studied here due to this limitation.

Despite the limitations of the study, the design and parameters investigated did reveal and reemphasize muscular coordination changes and the behavior of those changes for gait and gait transitions. Furthermore, the behavior of the coordination changed when investigating the preparation of a transition verses investigating locomotion beyond preferred conditions. As such future investigations should differentiate between the two designs. Other possible future directions of interest would be investigating both the preparation of transition and the recovery from transition as induced at different accelerations.
CONCLUSION

As previously established with reference to muscle coordination, stable locomotion and transition locomotion exhibit different coordination behaviors, and transitional specific muscular activity was observed in this study. More specifically, neuromuscular coordination changed steps before the observed gait transition. These changes were mainly present in the magnitude, duration, and timing of the muscle activation and exhibited non-linear behavior. The changing coordination behaviors exclusively appeared when inducing an actual transition via applying constant acceleration to vary the speed and were not observed within the same speed range as the transitions when speed was kept constant. These results suggest that changing velocity induces gait transition related behavior that cannot be observed with constant velocity in the same range.
REFERENCES


Figure A.A.1: GM Walking Correlation Trial Effects. Trial effect graph for the $R_0$ of the gluteus maximus' (GM) activity patterns of walking conditions. WC represents the constant velocity walking condition; WR represents the increased velocity walking condition that leads to a walk-to-run transition. Speed increased across trials 2 through 5 which were compared to the slowest trial, trial 1. For both conditions (WC & WR), the coefficient values decreased with the increased speed. There were no significant differences observed between the two conditions.
Figure A.A.2: GM Running Correlation Interaction. Condition/trial interaction graph for the R_0 of the gluteus maximus’ (GM) activity patterns of running conditions. Speed decreased across trials 2 through 5 which were compared to the fastest trial, trial 1. For the decreased velocity running condition that leads to a walk-to-run transition RW, the coefficient values decreased with the decreased speed indicating change of activity patterns. For running at constant velocity RC, the trend was different.
Figure A.A.3 GM Period 1 PeakM Interaction. Condition/trial interaction graph for the relative peak magnitude of the gluteus maximus’ (GM) first activity period. 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. Peak magnitude (PeakM) increased with speed (trials) in a quadratic fashion for WR and in a linear fashion for WC and RW. No significant trends were observed in RC.
Figure A.A.4: RF Walking Correlation Trial Effects. Trial effect graph for the $R_0$ of the rectus femoris’ (RF) activity patterns of walking conditions. WC represents the constant velocity walking condition; WR represents the increased velocity walking condition that leads to a walk-to-run transition. Speed increased across trials 2 through 5 which were compared to the slowest trial, trial 1. For both conditions (WC & WR), the coefficient values slightly decreased with the increased speed. There were no significant differences observed between the two conditions.

Figure A.A.5: RF Running Correlation Trial Effects. Trial effect graph for the $R_0$ of the rectus femoris’ (RF) activity patterns of walking conditions. RC represents the constant velocity running condition; RW represents the increased velocity running condition that leads to a run-to-walk transition. Speed decreased across trials 2 through 5 which were compared to the fastest trial, trial 1. For both conditions (RC & RW), the coefficient values exhibited a slight decrease with the decreased speed. However, the correlation values did remain high for both conditions, as such there were no significant differences observed between the two conditions.
Figure A.A.6: RF Period 1 PeakM Interaction. Condition/trial interaction graph for the relative peak magnitude of the rectus femoris’ (RF) first activity period. 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. Peak magnitude (PeakM) increased with speed (trials) in a quadratic fashion for WR and in a linear fashion for WC. No significant trends were observed in running (RC & RW).

Figure A.A.7: RF Period 1 Duration Interaction. Condition/trial interaction graph for the duration of the rectus femoris’ (RF) first activity period. 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. Duration (% of stride cycle) increased with speed (trials) linearly for WR and RC. Duration decreased linearly with speed in the RW condition. No significant trends were observed in WC.
Figure A.A.8: RF Period 2 PeakM Interaction. Condition/trial interaction graph for the relative peak magnitude of the rectus femoris’ (RF) second activity period. 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. Peak magnitude (PeakM) increased with speed (trials) linearly for all conditions (RW, WC, & WR) except one. No significant trends were observed in RC.
Figure A.A.9: VL Walking Correlation Trial Effects. Trial effect graph for the $R_0$ of the vastus lateralis' (VL) activity patterns of walking conditions. WC represents the constant velocity walking condition; WR represents the increased velocity walking condition that leads to a walk-to-run transition. Speed increased across trials 2 through 5 which were compared to the slowest trial, trial 1. For both conditions (WC & WR), the coefficient values decreased with the increased speed. There were no significant differences observed between the two conditions.

Figure A.A.10: VL Running Correlation Interaction. Condition/trial interaction graph for the $R_0$ of the vastus lateralis' (VL) activity patterns of running conditions. Speed decreased across Trials 2 through 5 which were compared to the fastest trial, trial 1. For the decreased velocity running condition that leads to a walk-to-run transition RW, the coefficient values decreased with the decreased speed indicating change of activity patterns. For running at constant velocity RC, the trend was different.
Figure A.A.11: VL Period 1 PeakM Interaction. Condition/trial interaction graph for the relative peak magnitude of the vastus lateralis’ (VL) first activity period. 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. Peak magnitude (PeakM) increased with speed (trials) in a linear fashion for all conditions (RW, WC, & WR) except one. No significant trends were observed in RC.

Figure A.A.12: VL Period 2 PeakM Interaction. Condition/trial interaction graph for the relative peak magnitude of the vastus lateralis’ (VL) second activity period. 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. Peak magnitude (PeakM) increased with speed (trials) in a quadratic fashion for WC and in a linear fashion for WR. No significant trends were observed in running (RC & RW).
Figure A.A.13: BF Walking Correlation Trial Effects. Trial effect graph for the $R_0$ of the biceps femoris’ (BF) activity patterns of walking conditions. WC represents the constant velocity walking condition; WR represents the increased velocity walking condition that leads to a walk-to-run transition. Speed increased across trials 2 through 5 which were compared to the slowest trial, trial 1. For both conditions (WC & WR), the coefficient values decreased with the increased speed. There were no significant differences observed between the two conditions.

Figure A.A.14: BF Running Correlation Interaction. Condition/trial interaction graph for the $R_0$ of the biceps femoris’ (BF) activity patterns of running conditions. Speed decreased across trials 2 through 5 which were compared to the fastest trial, trial 1. For the decreased velocity running condition that leads to a walk-to-run transition RW, the coefficient values decreased with the decreased speed indicating change of activity patterns. For running at constant velocity RC, the trend was different resulting in higher correlation values.
Figure A.A.15: TA Walking Correlation Condition & Trial Effects. Condition and trial effects graph for the $R_0$ of the tibialis anterior's (TA) activity patterns of walking conditions. WC represents the constant velocity walking condition; WR represents the increased velocity walking condition that leads to a walk-to-run transition. Speed increased across trials 2 through 5 which were compared to the slowest trial, trial 1. For both conditions (WC & WR), the coefficient values decreased with the increased speed. There were significant differences observed between the two conditions, but no significant interaction.

Figure A.A.16: TA Running Correlation Interaction. Condition/trial interaction graph for the $R_0$ of the tibialis anterior’s (TA) activity patterns of running conditions. Speed decreased across trials 2 through 5 which were compared to the fastest trial, trial 1. For the decreased velocity running condition that leads to a walk-to-run transition RW, the coefficient values decreased with the decreased speed indicating change of activity patterns. For running at constant velocity RC, the trend was different resulting in higher correlation values.
**Figure A.A.17: TA Period 1 PeakM Interaction.** Condition/trial interaction graph for the relative peak magnitude of the tibialis anterior’s (TA) first activity period. 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. Peak magnitude (PeakM) increased with speed (trials) in a linear fashion for all walking conditions (WR & WC). No significant trends were observed in running (RW & RC).

**Figure A.A.18: TA Period 1 Duration Interaction.** Condition/trial interaction graph for the duration of the tibialis anterior’s (TA) first activity period. 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. Duration (% of stride cycle) increased with speed (trials) in a linear fashion for all conditions (RW, RC, WC & WR).
Figure A.A.19: GAS Walking Correlation Trial Effects. Trial effects graph for the $R_0$ of the gastrocnemius’ (GAS) activity patterns of walking conditions. WC represents the constant velocity walking condition; WR represents the increased velocity walking condition that leads to a walk-to-run transition. Speed increased across trials 2 through 5 which were compared to the slowest trial, trial 1. For both conditions (WC & WR), the coefficient values decreased with the increased speed. There were no significant differences observed between the two conditions.

Figure A.A.20: GAS Running Correlation Interaction. Condition/trial interaction graph for the $R_0$ of the gastrocnemius’ (GAS) activity patterns of running conditions. Speed decreased across trials 2 through 5 which were compared to the fastest trial, trial 1. For the decreased velocity running condition that leads to a walk-to-run transition RW, the coefficient values decreased with the decreased speed indicating change of activity patterns. For running at constant velocity RC, the trend was different resulting in higher correlation values.
Figure A.A.21: GAS Period 1 PeakM Interaction. Condition/trial interaction graph for the relative peak magnitude of the gastrocnemius’ (GAS) single activity period. 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. Peak magnitude (PeakM) increased with speed (trials) in a linear fashion for all conditions (RC, RW, & WC) but one condition. PeakM increased quadratically with speed in the WR condition.

Figure A.A.22: GAS Period 1 Duration Interaction. Condition/trial interaction graph for the duration of the gastrocnemius’ (GAS) single activity period. 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. Duration (% of stride cycle) increased with speed (trials) in a linear fashion for all walking conditions (WC & WR). Duration decreased quadratically with speed in the RW condition. No significant trends were observed in RC.
Figure A.A.23: GAS Period 1 Offset Interaction. Condition/trial interaction graph for the offset of the gastrocnemius’ (GAS) single activity period. 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. Offset (% of stride cycle) decreased with speed (trials) in a linear fashion for all running conditions (RC & RW). Offset increased linearly with speed in the WR condition. No significant trends were observed in WC.
Figure A.A.24: SOL Walking Correlation Trial Effects. Trial effects graph for the R₀ of the soleus’ (SOL) activity patterns of walking conditions. WC represents the constant velocity walking condition; WR represents the increased velocity walking condition that leads to a walk-to-run transition. Speed increased across trials 2 through 5 which were compared to the slowest trial, trial 1. For both conditions (WC & WR), the coefficient values decreased with the increased speed. There were no significant differences observed between the two conditions.

Figure A.A.25: SOL Walking Correlation Trial Effects. Trial effects graph for the Rₘₐₓ of the soleus’ (SOL) activity patterns of walking conditions. WC represents the constant velocity walking condition; WR represents the increased velocity walking condition that leads to a walk-to-run transition. Speed increased across trials 2 through 5 which were compared to the slowest trial, trial 1. For both conditions (WC & WR), the coefficient values initially decreased slightly with the increased speed but then remained similar. There were no significant differences observed between the two conditions.
Figure A.A.26: SOL Walking Correlation Phase Shift Effect. Phase shift effect graph for the Per of the soleus’ (SOL) activity patterns of walking conditions. The Per parameter represents the distance along the stride cycle (%) that trial 1 was shifted to gain a higher correlation value with the comparison trial. WC represents the constant velocity walking condition; WR represents the increased velocity walking condition that leads to a walk-to-run transition. Speed increased across trials 2 through 5 which were compared to the slowest trial, trial 1. For both conditions (WC & WR), greater coefficient values were observed when shifting trial 1’s activity pattern to a period later in the gait cycle when the speed increased. There were no significant differences observed between the two conditions.
Figure A.A.27: SOL Running Correlation Interaction. Condition/trial interaction graph for the $R_0$ of the soleus’ (SOL) activity patterns of running conditions. Speed decreased across trials 2 through 5 which were compared to the fastest trial, trial 1. For the decreased velocity running condition that leads to a walk-to-run transition RW, the coefficient values decreased with the decreased speed indicating change of activity patterns. For running at constant velocity RC, the trend was different resulting in higher correlation values.

Figure A.A.28: SOL Running Correlation Interaction. Condition/trial interaction graph for the $R_{max}$ of the soleus’ (SOL) activity patterns of running conditions. Speed decreased across trials 2 through 5 which were compared to the fastest trial, trial 1. For the decreased velocity running condition that leads to a walk-to-run transition RW, the coefficient values decreased with the decreased speed indicating change of activity patterns. For running at constant velocity RC, the trend was different resulting in higher correlation values.
Figure A.A.29: SOL Running Phase Shift Effect. Phase shift effect graph for the Per of the soleus’ (SOL) activity patterns of running conditions. The Per parameter represents the distance along the stride cycle (%) that trial 1 was shifted to gain a higher correlation value with the comparison trial. Speed decreased across trials 2 through 5 which were compared to the fastest trial, trial 1. The constant velocity conditions for running is RC. RW represents the decreasing velocity running condition leading to a run-to-walk transition. For RW, greater coefficient values were observed when shifting trial 1’s activity pattern to a period later in the gait cycle when the speed decreased. For RC, greater coefficient values were observed when shifting trial 1’s activity pattern to an earlier period in the gait cycle when the speed decreased.
**Figure A.A.30: SOL Period 1 PeakM Interaction.** Condition/trial interaction graph for the relative peak magnitude of the soleus' (SOL) single activity period. 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. Peak magnitude (PeakM) increased with speed (trials) in a linear fashion for all conditions (RC, RW, & WC) but one condition. PeakM increased quadratically with speed in the WR condition.

**Figure A.A.31: SOL Period 1 Duration Interaction.** Condition/trial interaction graph for the duration of the soleus' (SOL) single activity period. 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. Duration (% of stride cycle) increased with speed (trials) in a linear fashion for all walking conditions (WC & WR). Duration decreased linearly for all running conditions (RC & RW).
Condition/trial interaction graph for the offset of the soleus’ (SOL) single activity period. 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. Offset (% of stride cycle) decreased with speed (trials) in a linear fashion for all running conditions (RC & RW). No significant trends were observed in the walking conditions (WC & WR).
APPENDIX B

EXAMINATION OF THE CONSISTENCY OF THE INDIVIDUAL EMG PROFILES

Specific examinations of the EMG profiles for the individual participants were conducted throughout the data processing. Featured in Appendix C are the EMG profiles of two subjects for a single muscle during the walking at constant velocity condition (WC) for trial 1 and the ensemble curve for the same condition and trial in order to demonstrate the consistent representation of the ensemble curves to the individual profiles.
**Figure A.B.1: EMG Profile 1.** Depicts the EMG profile of the gastrocnemius for subject 5 during the first walking trial at constant velocity (W1).

**Figure A.B.2: EMG Profile 2.** Depicts the EMG profile of the gastrocnemius for subject 11 during the first walking trial at constant velocity (W1).

**Figure A.B.3: Muscle Activity Pattern.** Depicts the ensemble curve of the gastrocnemius for all subjects during the first walking trial at constant velocity (W1).
APPENDIX C

CONSENT FORM

1. Study Title: Coordination of the lower extremity muscles during gait transitions.

2. Performance Sites: Louisiana State University

3. Investigators: 
   - Primary Investigator: Li Li, Ph.D.
   - Secondary Investigator: Lorna Ogden, B.Sc.
   - Department of Kinesiology
   - Department of Kinesiology
   - (225) 578-9146
   - (225) 388-4395

4. Purpose of the Study: To study the effects of manipulating speed on the neuromotor coordination of the lower extremity muscles during walking and running transitions.

5. Subjects: Study includes participants, who are free from any apparent gait abnormalities and who are free of any known cardiopulmonary dysfunctions: graduate and undergraduate Kinesiology students. The age range for participants is 18-35 years.

6. Number of Subjects: Sixteen participants are required for this study.

7. Description of Study: Participants will walk, run, or perform both on a motorized treadmill while surface EMG and position data are collected. The study requires at most two days of participation.

8. Benefits: The study will not directly benefit the participant, but does have implications in rehabilitation and neuromuscular theories.

9. Risks: There are minimal risks to the participant consisting of fatigue and fall. Instructions will be given to clarify the appropriate times to step on or off the treadmill thus reducing fall. To further reduce the risk of falling, the treadmill is equipped with handrails. To reduce fatigue or any other risks associated with moderate walking and running, incremental rest periods are included.

10. Right to Refuse: The experiment is on a voluntary basis, and at any time in the study the participant has the right to refuse participation or continuation of participation without any penalties.

11. Privacy: The study is confidential and participants will be given numbers to protect their identity. Any publication of the results will use the participants’ number instead of name. All association to the participant will not be released unless legally compelled.

12. Financial Information: No costs are incurred by the participants of this study.
“The study has been discussed with me and all my questions have been answered. I may direct additional questions regarding study specifics to the investigators. If I have questions about subjects' rights or other concerns, I can contact Robert Mathews, Chairman, LSU Institutional Review Board, (225) 388-8692. I agree to participate in the study described above and acknowledge the researchers' obligation to provide me with a copy of this consent form if signed by me.”

Participant’s Signature

Date
VITA

The author was born July 23, 1977, in Baton Rouge, Louisiana, to William and Dale Ogden. She and her younger sister, Shawnna Ogden, attended elementary and high school in the Baton Rouge Area before enrolling in Louisiana State University and Mechanical and Agricultural College. The author completed her Bachelor of Science degree in kinesiology with Honors College and University Honors in May 1999. The author entered the Graduate School at Louisiana State University and Mechanical and Agricultural College in August 1999. After which, she declared her program of graduate study emphasizing biomechanics in August 2000. With the completion of this thesis and satisfaction in all other degree requirements, the author obtained the degree of Master of Science for kinesiology in May 2002.