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An Electromyographical Analysis of the Role of Dorsiflexors on the Gait Transition During Human Locomotion

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Previous research has demonstrated that the preferred transition speed during human locomotion is the speed at which critical levels of ankle angular velocity and acceleration (in the dorsiflexor direction) are reached, leading to the hypothesis that gait transition occurs to alleviate muscular stress on the dorsiflexors. Furthermore, it has been shown that the metabolic cost of running at the preferred transition speed is greater than that of walking at that speed. This increase in energetic cost at gait transition has been hypothesized to occur due to a greater demand being placed on the larger muscles of the lower extremity when gait changes from a walk to a run. This hypothesis was tested by monitoring electromyographic (EMG) activity of the tibialis anterior, medial gastrocnemius, vastus lateralis, biceps femoris, and gluteus maximus while participants (6 M, 3 F) walked at speeds of 70, 80, 90, and 100% of their preferred transition speed, and ran at their preferred transition speed. The EMG activity of the tibialis anterior increased as walking speed increased, then decreased when gait changed to a run at the preferred transition speed. Concurrently, the EMG activity of all other muscles that were monitored increased with increasing walking speed, and at a greater rate when gait changed to a run at the preferred transition speed. The results of this study supported the hypothesis presented.

Key Words: walking, running, EMG, muscle activation

Introduction

Walking and running are the two most common gaits chosen by humans during terrestrial locomotion. Over level ground the speed of locomotion generally determines the gait that is chosen, with running being the gait of choice at higher speeds. Humans

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change gaits over a relatively narrow range of speeds, as demonstrated in a number of studies (Beuter & Lefebvre, 1988; Brisswalter & Mottet, 1996; Diedrich & Warren, 1995, 1998; Hreljac, 1993a, 1995a; Kram, Domingo, & Ferris, 1997; Mercier, Le Gallais, Durand, et al., 1994; Minetti, Ardigo, & Saibene, 1994; Thorstensson & Roberthson, 1987; Turvey, Holt, LaFiandra, & Fonseca, 1999) that have reported the preferred transition speed to be between 1.89 and 2.16 $m \cdot s^{-1}$. This speed range is well below the maximum walking speed of approximately 3.0 $m \cdot s^{-1}$ (Alexander, 1984, 1989), suggesting that factors other than physical limitations are responsible for the gait transition.

Although not verified experimentally, several researchers (Alexander, 1989; Cavagna & Franzetti, 1986; Grillner, Halbertsma, Nilsson, & Thorstensson, 1979; Heglund & Taylor, 1988; Hoyt & Taylor, 1981; McMahon, 1985) have suggested that gait transition during human locomotion is an energy saving mechanism. This has led to the unsubstantiated assumption that gait changes occur spontaneously at the energetically optimal transition speed. Recent experimental studies (Brisswalter & Mottet, 1996; Hreljac, 1993a; Minetti et al., 1994) have demonstrated, however, that gait transition actually occurs at speeds that are significantly lower than the energetically optimal transition speed, indicating that factors other than saving energy account for the transition.

It has been hypothesized (Thorstensson & Roberthson, 1987; Mercier et al., 1994) that the choice of transition speed during human locomotion is based on previous experience combined with feedback from peripheral receptors, since it is doubtful that energetic demands can be sensed by individuals in acute situations. Some animal studies (Biewener & Taylor, 1986; Farley & Taylor, 1991) have demonstrated that critical levels of kinetic factors such as vertical ground reaction forces and bone strain trigger gait transitions in several species, although no kinetic factors were found to be determinants of gait transition during human locomotion (Hreljac, 1993b). Besides forces applied to the human body, peripheral receptors of the lower limbs respond to a number of kinematic variables such as joint angular velocities and accelerations (Loeb & Levine, 1990). In a study examining the effect of various kinematic variables on the preferred transition speed during human locomotion, Hreljac (1995b) concluded that critical levels of ankle angular velocities and accelerations (in the dorsiflexor direction) triggered the walk-to-run gait transition; this led to the hypothesis that an important factor in changing gaits at the preferred transition speed is the prevention of stress in the dorsiflexor muscles.

Even though energetic cost has been found to be greater during running than during walking at the preferred transition speed (Brisswalter & Mottet, 1996; Hreljac, 1993a; Minetti et al., 1994), it has been observed (Hreljac, 1993a) that subjects perceive running to be easier than walking at the preferred transition speed, as measured by a rating of perceived exertion (Borg, 1973). At relatively low speeds of running (at or near the preferred transition speed), the larger muscles of the lower extremity are activated far below maximum levels (Nilsson, Thorstensson, & Halbertsma, 1985). Thus, the perception of exertion due to the muscular stress in these muscles should not be great. Since these muscles are composed of a large amount of metabolically active tissue compared to the dorsiflexors, they are likely to require more metabolic energy to sustain even low levels of activity than would be needed by the dorsiflexor muscles activated near maximal levels.

It is feasible that at walking speeds near the preferred transition speed, a conscious decision is made that a gait transition is desirable based on feedback from the dorsiflexor muscles. It is hypothesized that gait pattern is changed from a walk to a run in order to reduce muscular stress on the dorsiflexors while simultaneously placing more demand on the larger muscles of the lower extremity. The purpose of this study was to test this hypothesis by determining whether tibialis anterior (a major dorsiflexor muscle) muscle activity increases as walking speed increases, then decreases when gait changes to a run at the preferred transition speed, and concomitantly, whether the muscle activity of large lower extremity muscles increases with increased walking speed, and at a greater rate when gait changes to a run at the preferred transition speed.

Methods

Participants in this study were 9 healthy and physically active college students (6 M, 3 F), each of whom signed a university approved informed consent form reiterating the basic procedures and intent of the study and warning of any potential risks as a result of participation. All data were collected while the participants walked or ran on a motor-driven treadmill with speed controlled by the experimenter. A photocell timer was activated for 10 treadmill revolutions to monitor average treadmill speed whenever speed was being assessed. Participants who were inexperienced in treadmill locomotion were habituated by walking and running at various speeds on the treadmill for at least 15 minutes prior to the initiation of data collection. This time period has been shown to be sufficient to allow for accommodation to treadmill locomotion (Charteris & Taves, 1978; Schieb, 1986; Wall & Charteris, 1980, 1981).

To determine the preferred transition speed, the treadmill was initially set to a speed at which all participants could walk comfortably (approximately 1.25 $m \cdot s^{-1}$). After mounting the treadmill, the participant was given approximately 30 seconds (or longer if needed) to decide whether walking or running would be the preferred gait at this speed. The treadmill was then stopped to allow the participant to dismount and rest for as long as desired. At the initial speed setting, walking was everyone's preferred gait. Participants remounted after the treadmill speed was increased by approximately 0.1–0.2 $m \cdot s^{-1}$. A 30-s decision period was again allowed for the participant to indicate which gait would be preferred at the new treadmill speed. This procedure was repeated until the participant reached the speed at which running became the most natural gait, defined as the walk/run transition speed. This transition speed was determined by starting the treadmill at a high enough speed to ensure that participants would run, then decreasing the treadmill speed incrementally in a manner similar to that described above. The entire process was repeated three times in random order. The average of the walk/run and run/walk transition speeds was defined as the preferred transition speed.

After the preferred transition speed was determined, participants were instrumented with pre-amped, bipolar surface electrodes (Mini Beckman silver/silver chloride) in order to record electromyographic (EMG) activity of five muscles of the dominant leg: tibialis anterior (TA), medial gastrocnemius (GA), vastus lateralis (VL), biceps femoris (BF), and gluteus maximus (GM). Data were collected for 10 seconds at a sampling frequency of 500 Hz during five randomly ordered speed/gait conditions after an accommodation period of at least 2 minutes. The speed/gait conditions were walking at speeds of 70, 80, 90, and 100% of the preferred transition speed (W70, W80, W90, W100), and running at a speed of 100% of the preferred transition speed (R100). Participants were allowed as much rest time as desired between conditions. From the data collected at each speed/gait condition, five strides were randomly selected for analysis.

After full-wave rectification of the EMG signal of each muscle at all speed/gait conditions, a 100-ms moving average EMG activation level of each muscle was calculated for the five selected strides. Mean and peak 100-ms moving average activation levels were calculated for each of the five strides individually for all muscles at each speed/gait condition. The five-stride average of the mean and peak 100-ms moving average EMG signals at each speed/gait condition were normalized to the peak 100-ms moving average activation level for each muscle at the W100 condition. The mean and peak normalized 100-ms moving average EMG activation levels for each muscle were the dependent variables analyzed in this study. Subsequently, these variables will be referred to as the mean and peak normalized EMG activation levels.

A repeated-measures multivariate analysis of variance (MANOVA) compared average values of the mean and peak normalized EMG activation level of each muscle between the five speed/gait combinations (four walking speeds and one running speed). If the hypothesis tested was to be accepted, the value of the mean and peak normalized EMG activation level of the TA would increase as walking speed increased, then decrease for the running condition. The value of the mean and peak normalized EMG activation level of all other muscles would also increase as walking speed increased, but would then show a greater increase at the running condition. Specific preplanned single degree-of-freedom contrasts were set up to make comparisons between the values of the dependent variables at adjacent levels of the walking conditions. Comparisons were also made between the walking and running conditions at the preferred transition speed. For all comparisons, the level of significance was set at $\alpha = 0.05$.

Results

The average preferred transition speed was $1.94 \pm 0.20\ \text{m} \cdot \text{s}^{-1}$. To illustrate the general EMG activation pattern of muscles, the normalized 100-ms moving average EMG signals of each of the five muscles during the W100 (Figure 1a) and R100 (Figure 1b) conditions are shown. Graphs show the ensemble average curves for five strides of one representative participant. Time (horizontal axis) is expressed as a percentage of stride time, beginning and ending at heel strike.

Muscular stress on the dorsiflexors increased as walking speed increased, then decreased when gait changed to a run at the preferred transition speed. The peak normalized EMG activation level of the TA increased significantly between adjacent walking speed conditions, then decreased significantly from the W100 to the R100 conditions (Figure 2a). The mean normalized EMG activation level of the TA also increased with increased walking speed (Figure 2b), although there was no significant difference in the mean normalized EMG activation level of the TA between the W100 and R100 conditions.

For all muscles other than the TA, muscular stress tended to increase with increased walking speed, then increased at a greater rate when gait changed to a run at the preferred transition speed. The peak normalized EMG activation level of the VL,

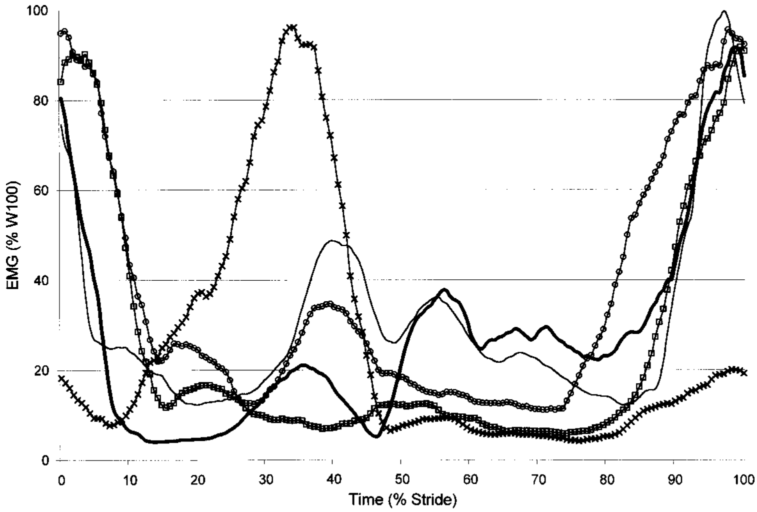

Figure 1a — Ensemble average curves (5 strides of one representative participant) of the normalized 100-ms moving average EMG signals of the GM (—), VL (– –), BF (–o–), MG (–x–), and TA (—) during the *W100* condition. Time (horizontal axis) is expressed as a percentage of stride time, beginning and ending at heel strike.

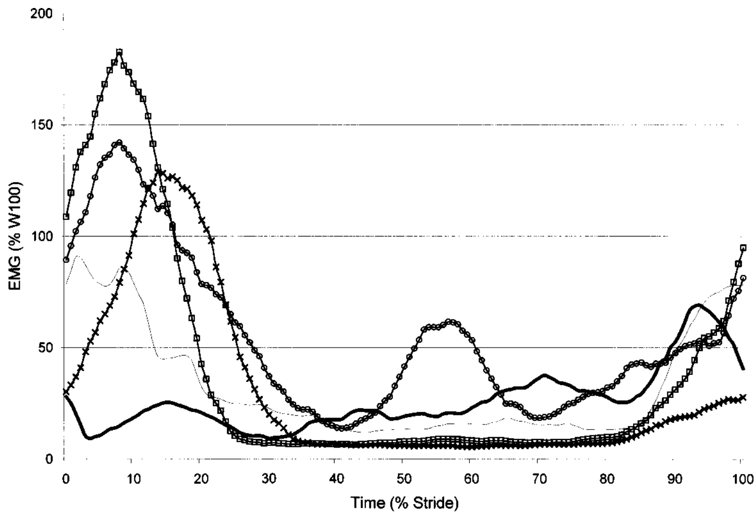

Figure 1b — Ensemble average curves (5 strides of one representative participant) of the normalized 100-ms moving average EMG signals of the GM (—), VL (– –), BF (–o–), MG (–x–), and TA (—) during the *R100* condition. Time (horizontal axis) is expressed as a percentage of stride time, beginning and ending at heel strike.

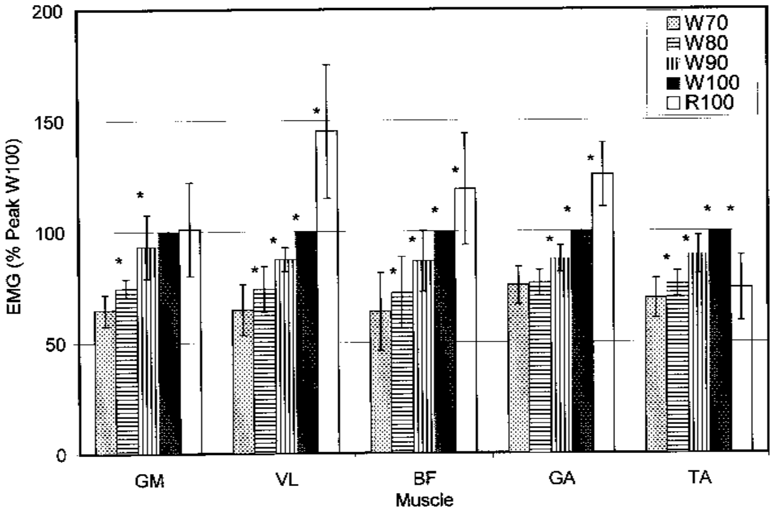

Figure 2a — Peak normalized EMG activation level of all muscles (± 1 *SD*). The activation level of the W100 condition is 100% for all muscles since values were normalized to the peak EMG levels of the W100 condition. * Significant difference, $p < 0.05$, between adjacent speed/gait conditions.

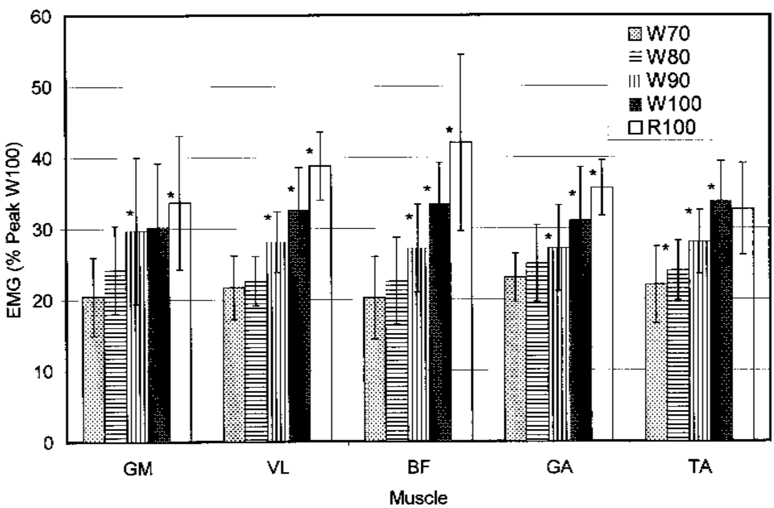

Figure 2b — Mean normalized EMG activation level of all muscles (± 1 *SD*). Values were normalized to the peak EMG activation level of the W100 condition for all muscles. * Significant difference, $p < 0.05$, between adjacent speed/gait conditions.

GA, BF, and GM all increased with increased walking speed, although not all increases between adjacent speed conditions were statistically significant (Figure 2a). The peak normalized EMG activation level of the VL, GA, and BF was significantly greater at the R100 condition than at the W100 condition. For the GM, no significant difference in the peak normalized EMG activation level was noted between the R100 and W100 conditions. For the VL, GA, BF, and GM muscles, the mean normalized EMG activation level also increased with increased walking speed, and was significantly greater during the R100 condition than for the W100 condition (Figure 2b).

Discussion

The pattern of peak normalized EMG activation level (Figure 2a) for all muscles closely followed the hypothesized pattern. For the TA, peak normalized EMG activity increased as walking speed increased, then decreased when gait changed to a run at the preferred transition speed. The peak normalized activation of the VL, GA, and BF all increased as walking speed increased, then increased further when gait changed from a walk to a run at the preferred transition speed. The peak normalized EMG activity of the GM increased as walking speed increased, but there was no difference in peak activation levels of the GM between walking and running at the preferred transition speed. When running at slow speeds, at or near the preferred transition speed, strides are actually shorter than when walking at fast speeds (at or near the preferred transition speed). Thus, the hips are not generally extended as much during the R100 condition as in the W100 condition.

Since the GM acts primarily as a hip extensor, it is likely that no large bursts of activity are required from this muscle when running at slow speeds. The mean normalized activation level of the GM, however, followed the same activation pattern as the other large muscles of the lower extremity (Figure 2b). That is, activation levels increased with increased walking speed, then increased further when gait changed to a run at the preferred transition speed. It appears that the shorter duration of the slow running stride compared to the fast walking stride requires that the GM be active for a greater percentage of the stride time during running (Figure 1b) than during walking (Figure 1a) at the preferred transition speed, although the level of activation is not high.

For the TA, mean normalized EMG activation levels increased as walking speed increased, but contrary to what was hypothesized, there was no significant decrease when gait changed from a walk to a run at the preferred transition speed. Moderate levels of TA activation are maintained throughout the running stride of the R100 condition, although it appears that no large bursts are required (Figure 1b). When walking at the preferred transition speed, large bursts of activation are required of the TA in the late swing and early stance phases. At other times the TA is relatively quiet (Figure 1a) during the W100 condition.

The results of the present study are fairly consistent with results reported previously. The preferred transition speed of the 9 participants of this study (1.94 ± 0.20 m $\cdot$ s^{-1}) was in the low end of the range of transition speeds reported in earlier studies (Beuter & Lefebvre, 1988; Brisswalter & Mottet, 1996; Diedrich & Warren, 1995, 1998; Hreljac, 1993a, 1995a; Kram et al., 1997; Mercier et al., 1994; Minetti et al., 1994; Thorstensson & Roberthson, 1987; Turvey et al., 1999). Similar to the present study, mean and peak EMG activity of the dorsiflexor muscles have been shown to increase as walking speed increases (Murray, Mollinger, Gardner, & Sepic, 1984; Shiavi, 1985; Shiavi, Champion, Freeman, & Griffin, 1981), whereas mean and peak values of EMG activity of the TA have been reported to be lower during running than for walking at speeds over 2.0 m · s^{-1} (Nilsson et al., 1985). Furthermore, mean and peak values of EMG activity of some larger muscles of the lower extremity have been shown to increase as walking speed increases (Ericson, Nisell, & Ekhom, 1986; Murray et al., 1984; Nilsson et al., 1985), in addition to being greater during running than during walking at speeds ranging from 1.0 to 3.0 m · s^{-1} (Nilsson et al., 1985).

When walking at the preferred transition speed, the EMG activation level of the TA was highest during the late swing and early stance periods, with relatively low TA activation levels noted during the largest portion of the stride time (Figure 1a). When running at the preferred transition speed, the TA remained active at a moderate level throughout most of the stride (Figure 1b). These patterns observed in TA activation may help explain why higher perceived exertion ratings were found during walking than for running at the preferred transition speed (Hreljac, 1993a). Since RPE is composed of a "local" and a "central" factor (Ekblom & Goldbarg, 1971; Noble, Metz, Pandolf, et al., 1973), it is possible that localized muscular stress in the dorsiflexors (including the TA) was perceived to be greater during walking due to the periodic high bursts of activity. Continuous moderate levels of muscle activation do not seem to produce the perception of undue muscular stress over a relatively short period.

The greater VO_2 noted during running at the preferred transition speed compared to walking at the preferred transition speed (Brisswalter & Mottet, 1996; Hreljac, 1993a; Minetti et al., 1994) could be explained by the higher mean and peak EMG activation levels of the larger muscles of the lower extremity when running at the preferred transition speed (Figures 2a and 2b). Since these muscles are composed of a large amount of metabolically active tissue, increases in activation levels would lead to elevated VO_2 readings. Although EMG activation levels were not compared to maximum voluntary contraction levels during the present study, it could be assumed that the EMG activation levels of these large muscles were not close to maximum when running at the slow pace of the preferred transition speed (Nilsson et al., 1985). At these moderate activation levels, muscular stress would be relatively low and would not likely be an important factor in the perception of exertion (measured by RPE), consistent with results reported earlier (Hreljac, 1993a).

The conclusions of earlier research (Hreljac, 1995b), which suggested that critical levels of ankle angular velocities and accelerations in the dorsiflexor direction precipitate the gait transition, are consistent with the results of the present study. When walking at speeds near the preferred transition speed, ankle dorsiflexor muscles would likely be experiencing a great deal of muscular stress when working close to maximum capacity to produce these large ankle angular velocities and accelerations.

As demonstrated in the present study, changing gaits at the preferred transition speed decreases the muscular stress on the dorsiflexors, as noted by the reduction of peak EMG activation of the TA falling from high to moderate levels. Concurrently, the demand placed on the larger muscles of the lower extremity increased from low to moderate levels. The cost of this performance tradeoff is an increase in metabolic energy required. It could be concluded that an important reason for humans to change gaits is to prevent overexertion and possible injury to the relatively small dorsiflexor muscles which are working close to maximum capacity when walking at speeds at or near the preferred transition speed.

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