The comparison of EMG characteristics and metabolic cost between walking and running near preferred transition speed

Ying-Ki FUNG*, Ming-Sheng CHAN**, Yin-Shin LEE* and Tzyy-Yuang SHIANG***

* Department of Physical Education, National Taiwan Normal University
162, Section 1, Heping E. Rd., Taipei City 106, Taiwan
**Division of Biokinesiology and Physical Therapy, The University of Southern California, Los Angeles, California, USA, 90089
***Department of Athletic Performance, National Taiwan Normal University
88, Sec. 4, Tingchou Rd., Taipei City 116, Taiwan
E-mail: tyshiang@gmail.com

Received: 3 October 2016; Revised: 23 January 2017; Accepted: 27 February 2017

Abstract
The purpose of this study was to determine the neuromuscular and metabolic changes among three selected preferred transition speeds (PTS) and two types of gait (walk and run). Twelve male subjects were enrolled to participate in this study. Vicon® motion capture system, Biopac® Electromyography and Cosmed® Indirect Calorimeter were used to determine the kinematics, neuromuscular control and metabolic expenditure, respectively. Subjects were asked to walk and run repeatedly under three different speed (75, 100, 125% PTS). The results show that thigh/shank iEMG ECC/CON ratio illustrates the metabolic change among different PTSs. A significant inefficient shank muscle activation was initially occurred under 100% PTS, furthermore thigh muscle became inefficient under 125% PTS. It is suggested that “muscle elastic capacity” may contribute to the changes in muscle activation between walking and running under different PTSs. During walking, the increase in walking speed may lead to decreased utilization of muscle elastic energy, whereas it is opposite the case for running. This study provides a different approach to clarify the unexplored area between physiological and neuromuscular system on PTS.

Key words: Electromyography, Muscle efficiency, Muscle elastic capacity, Metabolic expenditure, Locomotion

1. Introduction
Walking and running are the two fundamental movements in human locomotion. The differences between walking and running gaits are defined as the existence of the double support and flight phase during the gait cycle, respectively (Cappellini et al., 2006). Spontaneous change of gait speed while transitioning from walking to running, or vice versa, is determined as the preferred transition speed (PTS). In the past decade, the PTS was determined ranging from 5.2 km/h - 9.2 km/h in human gaits (Diedrich and Warren, 1995; Hreljac et al., 2005; Rotstein et al., 2005). When transitioning between the two gaits, individuals adapt the environmental changes by changing cadence, stride as well as muscle activation to meet the physiological and mechanical demands (Cappellini et al., 2006; Li et al., 1999). Based on the research purposes, previous literature primarily focused on computational modeling, kinematic and kinetic adaptation, muscular characteristics, determination of optimal and critical range of PTS as well as the effects between different experimental groups such as children, elderly or athletes (Chang, et al., 2014; Frost et al., 2002; Hreljac et al., 2005; Hreljac et al., 2002; Li and Ogden, 2012; Sasaki and Neptune, 2006). However, those studies only considered the PTS at a certain speed. It is suggested that running when the speed below 5.2 km/h and walking above 9.2 km/h is physically challenging.
To adapt to the environmental demands and return to proper homeostasis, individuals modify their gaits mechanically during the transitions (Diedrich and Warren, 1995). It has been shown that muscle contractions provide the mechanical energy required for the mechanical changes and the mechanical changes are correlated with metabolic energy (Sparrow and Newell, 1998). Metabolic expenditure (VO2) has been demonstrated to be higher if individuals walk at the transition speed to running than running at the same speed (Hreljac, 1995; Paróczai and Kocsis, 2006). While biomechanical changes suggest that mechanical demands may be responsible for the changes of gait speed (Diedrich and Warren, 1995), it is not clear how physiological demands would influence the initiation of these changes. No study has investigated muscular physiology changes to provide comprehensive information with respect to how individuals adapt to the physiological and mechanical demands. Therefore, the purpose of this study was to investigate the contributions of muscle activations to the changes in PTS by investigating the relationship between metabolic cost and muscle activations and their benefits to high speed walking and slow running during PTS.

2. Materials and Methods

2.1 Participants

Twelve male collegiate students (age: 24.50±1.88 yrs; height: 173.48±3.81 cm; weight: 72.69±8.50 kg) were enrolled in this study. All participants were free from chronic and cardiovascular problems. Written informed consent was obtained from each participant prior to the experiment.

2.2 Data collection and process

2.2.1 Pre-test

Pre-test was preceded at least two days before the experiment. The purpose of pre-test was to determine the PTS and VO2max.

2.2.1.1 PTS determination

The PTS determination referred to the procedure published in Rotstein’s study and was divided into two parts. In the first part, PTS from walking to running was determined. Participants performed walking with an initial speed of 5 km/h and the speed was gradually increased by 0.2km/h per minute. The PTS from walking to running (WtoR_PTS) was determined when the first flight phase appeared (gait transition). Participants then maintained running at the determined speed for 30 seconds in order to further confirm that the running speed was preferred. The test continued if it failed to determine the PTS. Next, to determine the PTS from running to walking (RtoW_PTS), participants performed running with an initial speed of 9 km/h and the speed was gradually decreased by 0.2 km/h per minute. The PTS from running to walking was determined when the flight phase disappeared. The averaged result between this two transition speeds was defined as the 100% PTS. The 100% PTS was calculated by following Eq. (1) (Rotstein, et al., 2005).

$$\frac{W_{toR\_PTS} + R_{toW\_PTS}}{2} = 100\%PTS$$

(1)

2.2.1.2 Maximum metabolic cost - VO2MAX

To understand the individual variation of cardiovascular capacity, VO2max test was used to determine the fitness level of the participants. All subjects were required to run on a treadmill to exhaustion. Exhaustion was determined using Bruce Protocol Test (Bruce, 1972). During the testing, VO2 max was monitored using Cosmed Ergospirometry System (Cosmed® Quark PFT, Italy) sampled at 1Hz.

2.2.2 Main experiment

Before the main experiment, participants warmed up on treadmill (series 2000 Treadmill, Marquette, WI, USA) with a speed between 3-5 km/h for 5-10 minutes and then performed maximal voluntary isometric contraction (MVC) to quantify maximal EMG output for the given electrode placement. The MVC test followed the SENIAM procedure (SENIAM, 1997). They were then asked to perform both 5 minutes walking and running in 3 selected speeds (75, 100 and 125% PTS) in a random order. The metabolic cost, Kinematics, and Electromyography (EMG) data during the last minute per trial were recorded. Three successful gait cycles (heel contact to heel contact) were averaged for each trial. Vicon motion capture system (10 cameras) sampled at 250 Hz (MX13+, Oxford, UK) was used to collect kinematic data. Kinematic data were used to identify the eccentric (ECC) and concentric (CON) phases of gait for the iEMG of
ECC/CON ratio calculation.

2.2.3 Data processing

Vicon Plug-In-Gait marker set was used to define the lower extremity coordinate system and the Plug-In-Gait model was used to calculate the kinematic data. The definition of ECC phases in this study was defined as the phase that the limb away the center of mass. Conversely, CON phase was defined as the phase that the limb toward the center of mass. The surface EMG signals were examined by Biopac MP150 EMG apparatus (MP150, Biopac, US) sampled at 1000 Hz. The examined muscles were rectus femoris (RF), Biceps Femoris Long Head (BF), Gastrocnemius (GA) and Tibialis anterior (TA) of the right lower extremity. Those four muscles were the primary activating muscles during walking and running (Mann & Hagy, 1980).

The raw EMG signals were bandpass filtered using 10-500 Hz cutoff frequency. The waveform of the CON and ECC phases were further integrated for calculating the average iEMG (iEMG/duration time) and the mathematical equation was as Eq. (2). The definition of $EMG(t)$ is the rectified EMG signal and $T$ is the time of the selected duration.

$$\frac{1}{T} \times \int_t^{t+T} EMG(t) dt = \text{average EMG} \quad (2)$$

ECC/CON ratio was defined as the ratio of ECC to CON phases of integrated electromyography (iEMG) obtained by the observed muscles (Aura & Komi, 1986). The iEMG of ECC/CON ratio (thigh and shank) were then compared among the speeds (75, 100 and 125% PTS) and two conditions (walk and run). Besides, to clarify the changes of ECC/CON ratio, an extended comparison for both thigh and shank muscle groups on eccentric and concentric phase was processed individually; in addition it was expressed in the form of %MVC by normalizing individual MVC.

The cost of locomotion was calculated by the Eq. (3)

$$Cost \ of \ Locomotion = \frac{net \ VO2}{Velocity} \quad (3)$$

Furthermore, the exercise VO2 (ml/kg/min) data was first minus to the mean of 5 minutes resting metabolic rate and then further divided by the individuals’ locomotion speed (m/min) in different trials.

2.2.4 Statistical analysis

SPSS version 15.0 was used to perform the statistical analyses (SPSS Inc., USA). The 2(Gait) x 3(PTS) ANOVA was used to determine the effect of Gait and PTS on the dependent variables and post-hoc paired t-tests were used for the pairwise comparisons. Furthermore, to determine the differences between each individual independent variable, for each main and interaction test, a post hoc pairwise comparisons and pair sample t-test would be further computed respectively. The significant level was set at $\alpha = .05$.

3. Results

3.1 PTS and VO2max

The PTS and VO2max of 12 participants were 6.86±0.29 km/h, and 49.80±6.52 ml/kg/min respectively.

3.2 The metabolic cost of locomotion

The metabolic costs during walking (Cw) and running (Cr) among three PTSs are presented in Figure. 1. There is a significant interaction between types of locomotion and percent PTSs, (F=86.26). This interaction effect showed that the metabolic cost between walking and running was different for 75, 100 and 125% PTS. Pairwise comparisons showed that Cr was significantly greater than Cw during 75 and 100% PTS, whereas Cw was significantly greater than Cr during 125%PTS.
3.3 %MVC (Eccentric phase)

The %MVC in thigh and shank during eccentric phase are presented in Table 1. There were significant interaction between types of locomotion and percent PTSs in both thigh and shank (F=13.46, F=20.51). The %MVC in the thigh (Eccentric phase) during running was significantly greater than walking at 75% PTS, whereas walking was significantly greater than running at 125% PTS. Moreover, there was no significant difference between walking and running at 100% PTS. The %MVC in the shank (Eccentric phase) during running was significantly greater than walking at 75% PTS, whereas walking was significantly greater than running at 125% PTS. There was no significant difference between walking and running at 100% PTS.

Table 1 The %MVC in the thigh and shank (eccentric phase) of walk and run among three PTS

| Locomotion speed | Thigh | Shank |
|------------------|-------|-------|
|                  | Walk  | Run   | Walk  | Run   |
| 75%PTS           | 14.62±5.77* | 19.95±7.52* | 19.77±6.16* | 39.32±18.64* |
| 100%PTS          | 20.85±7.08 | 23.23±8.00 | 43.17±21.96 | 32.25±17.58 |
| 125%PTS          | 39.95±15.25* | 24.56±10.39* | 79.85±29.01* | 30.93±9.31* |

* Significant differences between gaits in Thigh or Shank

3.4 %MVC (Concentric phase)

The %MVC in the thigh and shank during concentric phase are presented in Table 2. There was a significant interaction between type of locomotion and percent PTS (F = 5.26). The %MVC in the shank (Concentric phase) during running was significantly greater than walking at 75% PTS, whereas, there were no significant differences between walking and running at 100 and 125% PTS.

Table 2 The %MVC in the thigh and shank (concentric phase) of walk and run among three PTS

| Locomotion speed | Thigh | Shank |
|------------------|-------|-------|
|                  | Walk  | Run   | Walk  | Run   |
| 75%PTS           | 13.42±5.43 | 12.91±4.37 | 34.64±10.46* | 52.99±25.70* |
| 100%PTS          | 18.02±6.40 | 15.83±6.86 | 51.01±36.76 | 60.42±24.67 |
| 125%PTS          | 23.88±12.41 | 18.44±8.32 | 77.05±39.17 | 62.26±20.85 |

* The mean is significant different between type

3.5 iEMG ECC/CON ratio
The thigh and shank iEMG ECC/CON ratio during walking and running among three PTSs from the experimental results are presented in Figure 2. There were significant interactions between types of gaits and PTSs in both thigh and shank (F=10.75, F=13.72). Thigh iEMG ECC/CON ratio during running was significantly greater than walking at 75 and 100% PTS, whereas thigh iEMG ECC/CON ratio of walking was significantly greater than running at 125% PTS. There was no significant shank iEMG ECC/CON ratio difference between walking and running at 75% PTS, whereas shank iEMG ECC/CON ratio during walking was significantly greater than running at 125% PTS.

4. Discussion

The results in the present study were consistent with previous literature on PTS, demonstrating typical energetically optimal transition speed (EOTS) is located between 100% and 125% PTS (Hreljac, 1993; Hreljac et al., 2002). During walking, the metabolic cost was associated with the preferred transition speed. It appears that the metabolic cost increased when the speed increased during walking; however, the metabolic cost decreased when the speed increased during running. When considering the iEMG ECC/CON ratio, it appeared that the thigh iEMG ECC/CON ratio followed a similar trend with the metabolic cost between 100 and 125%PTS. The thigh iEMG ECC/CON ratio between walking and running merged between 100% and 125%PTS. As stated in the previous literature, iEMG ECC/CON ratio have been reported to be positively correlated with metabolic cost and muscle efficiency (Abe et al., 2007; Aura and Komi, 1986; Bourdin et al., 1995). Therefore, it is suggested that the thigh muscles group is more efficient walking at 75 and 100%PTS compared to 125%PTS. However, walking at 125%PTS is more inefficient when compared to running at 125%PTS. Furthermore, comparing the muscle activations in eccentric and concentric phases of the thigh separately, there were differences between walking and running at 75 and 100%PTSs (%MVC increased with the increased gait speed); however, the abruptly increase in muscle activation at 125%PTS during walking suggested a decreased muscle efficiency. When considering thigh %MVC (eccentric phase) between 100 and 125%PTS during running, participants appeared to have similar level of muscle activation, whereas, there was a continuous increase in muscle activation in the concentric phase. As a result, the thigh iEMG ECC/CON ratio decreased during running at 125%PTS.

According to iEMG, muscle efficiency of the thigh significantly changed at the 125%PTS are likely related to the muscle firing ratio due to the transition between eccentric and concentric phases (knee extension and flexion). For walking, increased thigh iEMG ECC/CON ratio was associated with the abrupt muscle activation during the eccentric phase from 100 to 125%PTS, while thigh iEMG ECC/CON ratio decreased due to the absence of further thigh muscle activation in the eccentric phase during running.

In addition, the shank iEMG ECC/CON ratios during walking and running merged between 75 and 100%PTS.
was different from the metabolic cost and thigh iEMG ECC/CON ratio. There was no statistical difference in iEMG ECC/CON ratio between walking and running at 75%PTS. On the contrary, significant higher shank iEMG ECC/CON ratio suggests that walking at 100 and 125%PTS is more inefficient when compared to running. When comparing the eccentric and concentric phase muscle activations at the shank. The trend was different between walking and running. Running in eccentric phase was a decent in percent MVC, whereas, there was ascent during concentric phase from 75 to 100%PTS, hence, it may result the decrease in Shank iEMG ECC/CON ratio or to keep shank muscle work efficiently for running during 100%PTS. Furthermore, due to the shank iEMG ECC/CON ratio remained the same during walking and running between eccentric and concentric phases, the shank iEMG ECC/CON ratio at 125%PTS was similar to 100%PTS. The muscle efficiency of shank muscles significantly changed during/after 100%PTS and just like the result of thigh iEMG ECC/CON ratio, it seems likely related to the muscle firing ratio due to the change of eccentric and concentric phase (ankle plantar and dorsiflexion). For walking, increased shank iEMG of ECC/CON ratio associated with the abrupt muscle activation in the eccentric phase from 75% to 100%PTS, while shank iEMG ECC/CON ratio decreased due to the absence of further shank muscle firing during eccentric phase for running.

Although there was no difference in metabolic cost among PTSs in walking and running, the metabolic cost increased with increased walking speed. However, the metabolic cost decreased with increased running speed during running. In the present study, we assumed that the examined muscle groups were responsible for walking and running. Hence, it is suggested that the changes of metabolic cost from 75 to 100%PTS was due to the inefficient activation on shank muscles (Cr – decrease; Cw - increase). Furthermore, the inefficient activation for thigh muscles further influenced the overall metabolic cost of locomotion between 100 to 125%PTS.

In the past two decades, researchers explored the walking and running economy (Brisswalter et al., 1998; Daniels and Daniels, 1992; Daniels, 1985; KyrÖLÄInen et al., 2001; Martin et al., 1993; Williams and Cavanagh, 1987); however, those findings did not fully explain the individual differences in metabolic cost at a selected speed. Thus, more recent scientists tried to quantify elastic storage of energy to illustrate the muscle efficiency by investigating iEMG ECC/CON ratio (Abe et al., 2007; Bourdin et al., 1995). This concept was then further described as the “muscle elastic capacity”. From the two classical literatures (Aura and Komi, 1986; Bosco et al., 1982), the authors suggested that the increased iEMG of ECC/CON ratio is indicative of increased utilization of muscle elastic energy, and vice versa. In the present study, shank muscle showed a major change for the muscle elastic capacity from 75 to 100%PTS. At the 100%PTS, the shank utilized more muscle elastic energy compared to 75%PTS during walking, while it utilized less muscle elastic energy in running at 100%PTS compared to 75%PTS. In addition, thigh muscles showed a major change for the muscle elastic capacity from 100 to 125%PTS. The thigh utilized more muscle elastic at 125%PTS compared to 100%PTS during walking, while it is lower in running at 125%PTS compared to 100%PTS. It is suggested that the higher muscle elastic energy during walking at 100 and 125%PTS is attributed to a stiffer lower extremity during fast walk due to the pendulum theory demonstrated in gait.

5. Conclusion

This study illustrated that there were differences in muscle mechanical efficiency across 3 selected %PTS between walking and running. Shank muscles exhibited a significant inefficiency during walking compared to running between 75 and 100%PTS. However, shank muscle was more efficient during running compared to walking between 75 and 100%PTS. Furthermore, the thigh muscles showed a significant inefficiency during walking compared to running between 100% and 125%PTS, while the thigh muscles were more efficient during running compared to walking between 100% and 125%PTS. When considering the metabolic cost, the inefficient activations for shank muscles may affect the metabolic cost between 75 and 100%PTS (increased Cw and decreased Cr). Moreover, the inefficient activations for thigh muscles may affect the metabolic cost between 100 and 125%PTS (increased Cw and decreased Cr and EOTS). These results suggest that more “muscle elastic capacity” is utilized when speed increases in walking but not in running. The increased speed during walking may contribute to decreased ability to utilize the muscle elastic energy, whereas it is not the case for running.

Acknowledgements

This study was funded by “Aim for the Top University Project” of the National Taiwan Normal University and the Ministry of Education, Taiwan, R.O.C.
References

Abe, D., Muraki, S., Yanagawa, K., Fukuoka, Y., and Niihata, S., Changes in EMG characteristics and metabolic energy cost during 90-min prolonged running, Gait & Posture, Vol.26, No.4 (2007), pp.607-610.
Aura, O., and Komi, P. V., Mechanical efficiency of pure positive and pure negative work with special reference to the work intensity, International Journal of Sports Medicine, Vol.7, No.01 (1986), pp.44-49.
Bosco, C., Ito, A., Komi, P. V., Luhtanen, P., Rahkila, P., Rusko, H., and Viitasalo, J. T, Neuromuscular function and mechanical efficiency of human leg extensor muscles during jumping exercises, Acta Physiologica Scandinavica, Vol.114, No.4 (1982), pp.543-550.
Bourdin, M., Belli, A., Arsac, L. M., Bosco, C., and Lacour, J. R., Effect of vertical loading on energy cost and kinematics of running in trained male subjects, Journal of Applied Physiology, Vol.79, No.6 (1995), pp.2078-2085.
Brisswalter, J., Fougeron, B., and Legros, P., Variability in energy cost and walking gait during race walking in competitive race walkers, Medicine and Science in Sports and Exercise, Vol.30, No.9 (1998), pp.1451-1455.
Bruce, R. A., Multi-stage treadmill test of maximal and sub maximal exercise. In: AHA (Ed.), Exercise testing and training of apparently health individuals: A handbook for physicians (1972), pp.32-34, American Heart Association.
Cappellini, G., Ivanenko, Y. P., Poppele, R. E., and Lacquaniti, F., Motor patterns in human walking and running. Journal of Neurophysiology, Vol.95, No.6 (2006), pp.3426-3437.
Chang, Y. C., Hsieh, C. F., Chen, C. H., Shiang, T. Y., The effect of forefoot flexibility on metatarsophalangeal joint and lower extremity muscle activation, Physical Education Journal, Vol. 47, No. 2 (2014), pp.179-185.
Daniels, J., and Daniels, N., Running economy of elite male and elite female runners, Medicine and Science in Sports and Exercise, Vol.24, No.4 (1992), pp.483-489.
Daniels, J. T., A physiologist's view of running economy, Medicine and Science in Sports and Exercise, Vol.17, No.3 (1985), pp.332-338.
Diedrich, F. J., and Warren Jr, W. H., Why change gaits? Dynamics of the walk-run transition, Journal of Experimental Psychology: Human Perception and Performance, Vol.21, No.1 (1995), pp.183-202.
Frost, G., Bar-Or, O., Dowling, J., and Dyson, K., Explaining differences in the metabolic cost and efficiency of treadmill locomotion in children, Journal of Sports Sciences, Vol.20, No.6 (2002), pp.451-461.
Hreljac, A., Preferred and energetically optimal gait transition speeds in human locomotion, Medicine and Science in Sports and Exercise, Vol.25, No.10 (1993), pp.1158-1162.
Hreljac, A., Effects of physical characteristics on the gait transition speed during human locomotion, Human Movement Science, Vol.14, No.2 (1995), pp.205-216.
Hreljac, A., Imamura, R., Escamilla, R. F., Casebolt, J., and Sison, M., Preferred and energetically optimal transition speeds during backward human locomotion, Journal of Sports Science and Medicine, Vol.4, No.4 (2005), pp.446-454.
Hreljac, A., Parker, D., Quintana, R., Abdala, E., Patterson, K., and Sison, M., Energetics and perceived exertion of low speed running and high speed walking, Facta universitatis-series: Physical Education and Sport, Vol.1, No.9 (2002), pp.27-35.
KyrÖläÎnen, H., Belli, A., and Komi, P. V., Biomechanical factors affecting running economy, Medicine and Science in Sports and Exercise, Vol.33, No.8 (2001), pp.1330-1337.
Li, L., and Ogden, L. L., Muscular activity characteristics associated with preparation for gait transition, Journal of Sport and Health Science, Vol.1, No.1 (2012), pp.27-35.
Li, L., van den Bogert, E. C. H., Caldwell, G. E., van Emmerik, R. E. A., and Hamill, J., Coordination patterns of walking and running at similar speed and stride frequency, Human Movement Science, Vol. 18, No. 1 (1999), pp.67-85.
Mann, R. A., and Hagy, J., Biomechanics of walking, running, and sprinting, The American Journal of Sports Medicine, Vol. 8, No. 5 (1980), pp.345-350.
Martin, P. E., Heise, G. D., and Morgan, D. W., Interrelationships between mechanical power, energy transfers, and walking and running economy, Medicine and Science in Sports and Exercise, Vol. 25, No. 4 (1993), pp.508-515.
Paróczai, R., and Kocsis, L., Analysis of human walking and running parameters as a function of speed, Technology
and Health Care, Vol. 14, No. 4 (2006), pp.251-260.
Rotstein, A., Inbar, O., Berginsky, T., and Meckel, Y., Preferred transition speed between walking and running: Effects of training status, Medicine and Science in Sports and Exercise, Vol. 37, No.11 (2005), pp.1864-1870.
Sasaki, K., and Neptune, R. R., Muscle mechanical work and elastic energy utilization during walking and running near the preferred gait transition speed, Gait & Posture, Vol. 23, No. 3 (2006), pp.383-390.
Sparrow, W. A., and Newell, K. M., Metabolic energy expenditure and the regulation of movement economy, Psychonomic Bulletin and Review, Vol. 5, No.2 (1998), pp.173-196.
Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles: European Applications of Surface ElectroMyoGraphy, SENIAM, available from <http://www.seniam.org/>, (accessed on June, 1997).
Williams, K. R., and Cavanagh, P. R., Relationship between distance running mechanics, running economy, and performance, Journal of Applied Physiology Vol. 63, No.3 (1987), pp.1236-1245.