A preliminary study suggests that walk-to-run transition is consistent with mechanical optimization

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1. Introduction

In spite of the apparent simplicity, the organization of the neuromusculoskeletal system during complex movements remains poorly understood in humans. One explanation is that the motor system is redundant: a given movement can be realized using different muscles and joint activity patterns (Bernshteĭn 1967). Some theories, such as optimal control or motor primitives, explain this conundrum which pertains to very basic movements, such as grasping or pointing. However, to the author's knowledge, no cost functions have investigated the walking and running coordination during locomotion. While walking is commonly observed at low speed (Froude = Fr = v^2 / gl < 0.5; with v the speed, g the gravity and l the CoM height) and running at high speed, it remains unknown whether a mechanical cost function can explain the change of gait observed. Furthermore, the trigger of the walk-to-run transition has yet to be determined. Classical optimization rules have previously revealed underlying organization of human motion: minimum torque, minimum kinetic energy, or minimum jerk (Flash & Hogan 1985) can predict kinematics of the segments. Similarly, Gonzales and Hull (1989) proposed that a moment cost function (MCF) based on lower limb's joint moments may be a criterion to optimize bicycle settings and pedaling cadence. Using this criterion, Marsh et al. (2000) have shown a link between minimization of the MCF and preferred cycling cadence. Likewise, Poirier et al. (2007) have shown that this criterion can explain the sit-to-stand transition in cycling.

Therefore, the aim of this study was to compute MCF at different walking and running speeds. We hypothesized that MCF would be optimal at low speeds during walking and at high speeds during running.

2. Methods

2.1. Participants and materials

Nineteen healthy men (23 ± 5 y; 1.79 ± 0.07 m; 80.7 ± 11 kg) participated in this experimentation.

They were equipped with 42 reflective markers recorded by 12 optoelectronic cameras sampled at 200 Hz (VICON, Oxford's metrics, Oxford, UK). The participants performed barefoot walking and running tests on a treadmill (PF 500 CX, PRO FORM, Villepreux, France) mounted on a large force platform recording at 1 kHz (AMTI, Watertown, MA, USA). The kinematic and kinetic data were filtered with a 4th-order zero-lag Butterworth filter and with a 6 and 10 Hz cut-off frequency, respectively.

2.2. Experimentation

The participants were asked to walk and run with their preferred step frequency at 0.56, 1.11, 1.67, and 2.22 m s^{-1} and 1.67, 2.22, 2.78, 3.33, 3.89, and 4.44 m s^{-1}, respectively. From these tests, Fr was computed for each speed stage i and each participant j as:

$$\mathrm{Fr}_{ij} = \frac{v_i^2}{g \cdot l_j}$$

2.3. Assessed parameters

In the present study, the human body was considered as a whole of 16 rigid body segments (de Leva 1996). The functional centers of rotation of the hips were determined using the SCoRE method.

Merging kinematics, kinetic, and anthropometric data according to de Leva (1996), a Newton–Euler recursive algorithm was used to perform a bottom-up inverse dynamics protocol in order calculate 3D joint moments

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at the ankles, knees, and hips. The MCF was then computed as:

$$\mathrm{MCF} = \frac{1}{N}\sum_{i=1}^{N}\sum_{j=\mathrm{left}}^{\mathrm{right}}[||\mathbf{M_A}(ij)|| + ||\mathbf{M_K}(ij)|| + ||\mathbf{M_H}(ij)||]$$

where $\mathbf{M_A}(ij), \mathbf{M_K}(ij)$, and $\mathbf{M_H}(ij)$ are the three-dimensional joint moments at ankle, knee, and hip at the ith frame and j side, and N is the frame number during one gait cycle. The MCF was expressed in a dimensionless form as $\mathrm{MCF^D}$ to remove the anthropometric effects from CoM height (l), body mass (m), and gravity (g): $\mathrm{MCF^D} = \mathrm{MCF}/(\mathrm{lmg})$ (Villeger et al. 2014).

2.4. Statistics

$\mathrm{MCF^D}$ was calculated for each condition ($\mathrm{MCF^D_R}$ and $\mathrm{MCF^D_W}$ for running and walking, respectively) and at each speed stage. Linear regressions were calculated for both locomotion modes to express the dimensionless MCF according to Fr.

3. Results and discussion

$\mathrm{MCF^D_R}$ and $\mathrm{MCF^D_W}$ at each speed stage are presented in Figure 1.

For each condition, linear regressions were:

$$\mathrm{MCF^D_W} = 0.263\ \mathrm{Fr} + 0.259 \quad (R^2 = 0.67)$$

$$\mathrm{MCF^D_R} = 0.075\ \mathrm{Fr} + 0.352 \quad (R^2 = 0.64)$$

Our results showed that MCF is lower when walking at Fr < 0.49 and during running at higher values of Fr. Although no spontaneous speed transition was determined in this study, this result is close to the spontaneous dimensionless transition speed value reported in the literature: according to Alexander (1989), the walk-to-run transition occurred at Nfr = 0.48 This therefore suggests that our participants were likely to minimize their MCF during gait.

While previous studies proposed that the metabolic energy consumption is not optimal because the preferred transition speed is lower than the optimal transition speed (Tseh et al. 2002), our results confirm that the MCF, a mechanical-based criterion, appears to be a relevant parameter and can predict the locomotion pattern. Otherwise, MCF criterion is computed from joint moments and directly linked with muscular efforts at lower limbs, which have been prove to be well perceived by the central nervous system (Windhorst 2007). Other authors suggest that the determinants of the walk-to-run transition can be instantaneous values like peak moment, peak power (Pires et al. 2014) or peak force (Raynor et al. 2002). Here, MCF is consistent with global optimization as it takes into account whole joint moments at lower limbs during one gait cycle.

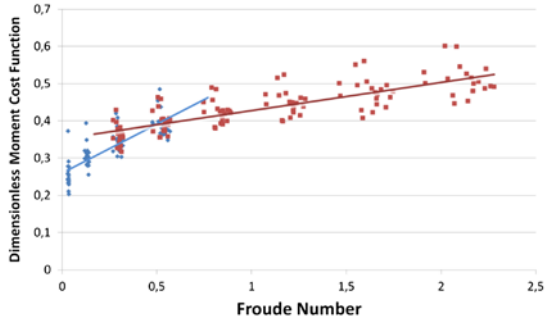

Figure 1. Dimensionless moment cost function according to Froude number (walking condition in blue and running in red).

Thus, the MCF must also be considered carefully as it does not take into account the travelled distance. It integrates joint moments during one cycle whose duration is not the same between walking and running. To summarize, the present study shows that the walk-to-run transition optimizes MCF for the duration of one cycle.

4. Conclusions

This study aimed to determine a cost function which could explain the walk-to-run transition. In accordance with optimal control theory, the present data suggest that the MCF may trigger the walk-to-run transition.

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