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Segment-interaction and its relevance to the control of movement during sprinting

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ABSTRACT

The aims of this study were to investigate the functions of muscle torque and its relation to other torque components during sprinting stance and swing phases. Three-dimensional kinematics and ground reaction force data were collected from eight elite male sprinters performing maximal-effort sprinting on a synthetic track. Intersegmental dynamics approach (ISD) was used to quantify lower extremity joint torque and their components during one gait cycle of the maximal speed phase during sprinting. Specifically, a modified version of the ISD was used to determine the relationship among the active muscle torque (MST), passive motion-dependent torque (MDT), ground reaction torque (EXT), gravitational torque (GTT), and net joint torque (NET) during stance and swing phases. The contribution of each torque component to lower extremity joint motion was quantified. Our results revealed that the active MST functioned to counteract EXT during stance phase. EXT acted to accelerate knee extension and hip flexion, meanwhile the muscles across these joints produced flexion torque at the knee and extension torque at the hip. During swing phase, MDT at the knee and hip joints was mainly produced by leg angular acceleration which was very significant at the moment when leg swing from forward to backward, active MST counterbalanced the effect of MDT. In summary, muscle torque functions mainly to push the ground to counter ground reaction force for controlling the movement during stance phase. However, the role of muscle torque changes during swing phase to mainly counteract the effect of MDT to control the movement direction of the lower extremity at both the hip and knee joints.

1. Introduction

Movements of the lower extremities are controlled by a complex combination of active muscle torque and passive torque created by contact forces, motion dependent forces and gravitational forces. Muscle torque was generated within the body but modulated by the body's interaction with the environment. Coordinated and skilled movements involves optimization of the interactions between muscle torque and other torque (Bernstein, 1967). Zernicke and colleagues (Zernicke et al., 1991; Zernicke and Schneider, 1993; Zernicke, 1996) considered that these active and passive torques can be quantified by using intersegmental dynamics (ISD) and that the quantification of these torques is important for better understanding the role of the central nervous system in coordinating muscular torque during movements.

ISD has been widely used to study movement control in different situations such as walking (Putnam, 1993; Ganley and Powers, 2006), running (Hunter et al., 2004), jumping (Kim and Kim, 2011) and different kinds of arm movements (Dounskaia et al., 2002; Kodek and Munih, 2003; Hirashima et al., 2008; Kim et al., 2009; Gritsenko et al., 2011; Wang et al., 2012). It has also been used to study multi-joint movement control for patients with cerebellar dysfunction (Bastian et al., 1996; Bastian et al., 2000; Morton et al., 2004). These studies suggest that the effects of muscle torque (MST) and their interaction with the environment are affected by the speed of movement. The main function of MST is to counteract the external torque due to ground reaction force (EXT) during stance phase of running (Mann and Sprague, 1980; Mann, 1981; Hunter et al., 2004). Interactions between muscle torque and motion dependent torque (MDT) become gradually more pronounced with increasing speed in both upper and lower extremity movements (Zernicke, 1996).

According to Winter (2009), in spite of fact that muscle moment signal has mechanical units (N m), “we must consider the moment signal as a neurological signal because it represents the final desired central nervous system (CNS) control”. Lower extremity muscles generate fast movements during swing phase and withstand considerable ground reaction forces during stance (Wood, 1987). Study of the relationships between intersegmental torque and their effects in the lower extremity joints can help us to

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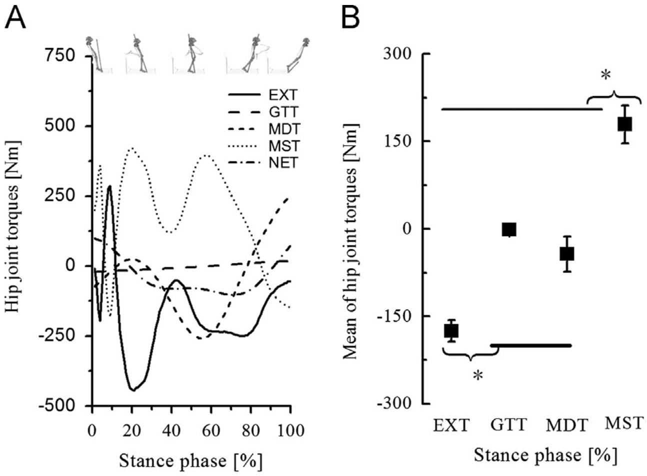

Fig. 1. (A) Ensemble curves of hip joint torques during stance phase, (EXT: ground reaction torque; GTT: gravitational torque; MDT: motion dependent torque; MST: muscle torque; NET: net joint torque). (B) The mean and standard deviation (error bars) of EXT, GTT, MDT and MST at the hip joint during stance phase. * Indicates a statistically significant difference between the mean of hip joint torques ($P<0.0001$) where horizontal bar indicates homogenous groups. MST was significantly greater than the other three components. EXT was significantly less than GTT and MDT among the three. (+: Extension torque, −: flexion torque.)

understand movement control during sprinting. Furthermore, it can also help us to gain insights into the function of the lower extremity muscles during the stance and swing phases. Zernicke et al. (1991) suggested that the main function of MST was to counteract MDT during swing phase of running. Hunter et al. (2004) suggested that MST acted mainly to counterbalance the effects of EXT during sprinting stance phase.

Therefore, the purpose of this study was to investigate the function of MST, and its relations to other torque components during sprinting stance and swing phases. We hypothesized that MST functioned mainly to counteract EXT during stance phase due to the interaction with the ground, but that MST acted principally to counteract MDT during swing phase in the absence of ground reaction forces.

2. Methods

2.1. Subjects

Eight male elite sprinters participated in the study (age: 21.1 ± 1.9 years, mass: 74.7 ± 4.1 kg, height: 181.5 ± 3.9 cm). Their best personal performance for 100 m ranged from 10.27 to 10.80 s. They were free of lower extremity musculoskeletal injuries at least 6 months prior to the study. The study was approved by the local ethical committee. Each subject signed an informed consent forms after all questions were answered satisfactorily.

2.2. Data collection

The subjects performed maximal-effort sprints on a synthetic track. All subjects wore spiked shoes. Three-dimensional kinematics data were collected at a sampling rate of 300 Hz from eight high resolution cameras (Vicon, Oxford, UK). The calibration volume for kinematic data collection was $10.0\times2.5\times2.0$ m and centered 40 m from the sprint start line. A recessed Kistler force-plate (60×90 cm) (Kistler 9287B, Kistler Corporation, Switzerland) was used to measure the ground reaction force (GRF). It was covered with track type of material and located about 40 m from the sprint starting line. Force signals were than amplified and recorded by the Vicon System at a sampling rate of 1200 Hz. Each sprinter performed three trials with sufficient rest intervals, all trials in which no markers dropped and either foot of the subject successfully hit the force plate were analyzed.

2.3. Data reduction

Pre-processed kinematics and kinetic data (C3D file) were then imported to Visual 3D (3.390.23, C-Motion Inc., U.S.A.). In the current study, Visual 3D was used to filter the data. Specifically, Kinematic and force data were filtered through a fourth-order Butterworth digital filter at cut-off frequency 17 (Yu, 1989) and 55 Hz (Winter, 2009). The average horizontal velocity of the body center of mass during the whole stride cycle was used to represent the running speed.

A running gait cycle was defined from consecutive foot touchdowns during the sprinting. Stance phase was defined from the foot touchdown to toe-off as measured by the force platform, whereas swing phase was defined as from the toe-off to foot touchdown. We have divided both stance and swing phases temporally into quintiles to facilitate the analysis.

Anatomical landmarks and segments were defined according to the Visual 3D framework model and the anthropometric data. The whole body center of mass was determined using a fourteen-segment model (Hay, 1993). The anthropometric inertial parameters for Chinese adults published by Zheng (2007) were used to determine the location of center of mass and the moment of inertia of each body segment.

The intersegmental dynamics analysis was conducted by a customized program based on ISD formulation and by inputting limb kinematics, anthropometric data and GRF. In detail, to calculate the active muscle torque and the dynamic interactions among the thigh, leg and foot, the lower limb model in our earlier studies (Jin et al., 2008; Liu et al., 2009) was used. Based on Zernicke's work (1996), torque at each joint can be separated into five categories: net joint torque, gravitational torque, motion-dependent torque, contact torque (termed as ground reaction torque in this study) and muscle torque, with the first category being the sum of the rest:

$$\begin{aligned}\text{Net joint torque (NET)} = {} & \text{generalized muscle torque (MST)}\\ & +\text{gravitational torque (GTT)}\\ & +\text{ground reaction torque (EXT)}\\ & +\text{motion dependent torque (MDT)}\end{aligned}$$

NET is the sum of all the torque components acting at a joint. MST is mainly generated by muscle contractions. GTT results from gravitational forces acting at the center of mass of each segment. EXT is generated at joints by ground reaction force acting on the foot. MDT arises from the mechanical interactions occurring between limb segments, and is the sum of all motion dependent torque produced by segment movements, e.g. angular velocity and angular acceleration of segments.

Joint torques, and their components, changes rapidly during both stance and swing phases (See Figs. 1,2,4 and 5A for examples). These rapid development lead to variability among individuals and from trial to trial. Furthermore, kinematic changes are largely due to the accumulate effects of torque, such as impulse momentum relationship, rather than instantaneous force at any given moment. To account for this rapid change and enable detailed discussion, we further divided the joint torque trajectories during stance and swing phases into quintiles. This method enable us to further compare and contrast the mechanical actions during both stance and swing phases sprinting gait cycle.

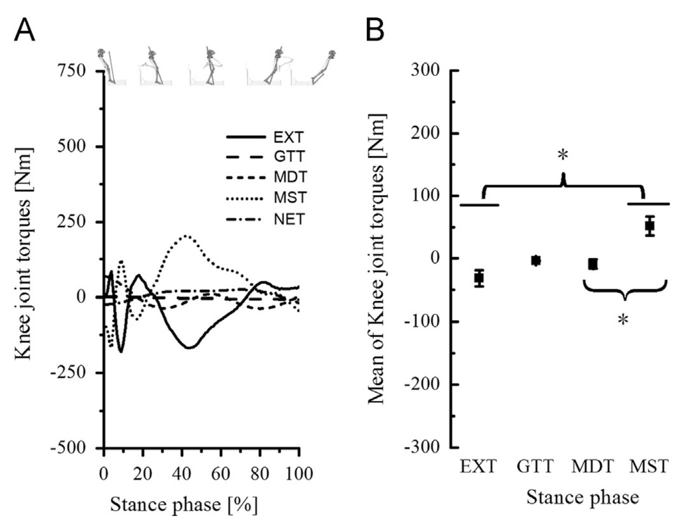

Fig. 2. (A) Ensemble curves of knee joint torques during stance phase (EXT: ground reaction torque; GTT: gravitational torque; MDT: motion-dependent torque; MST: muscle torque; NET: net joint torque). (B) The mean and standard deviation (error bars) of EXT, GTT, MDT and MST in the knee joint during stance phase. * Indicates a statistically significant difference between the mean of knee joint torques ($P<0.0001$). MST was significantly greater than EXT MDT. (+: Extension torque, −: flexion torque.)