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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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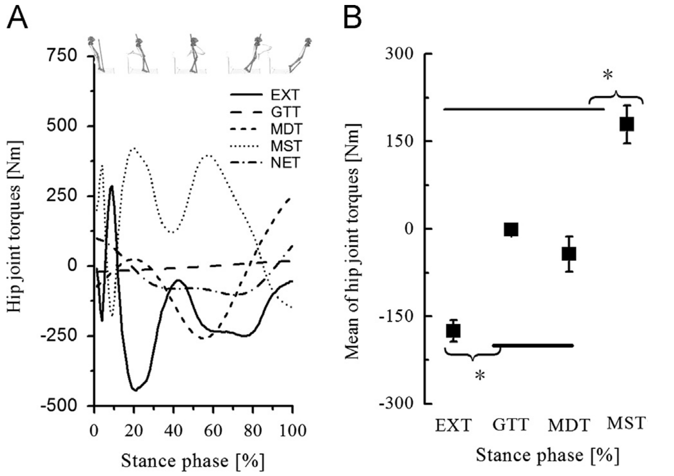

Fig. 1. (A) Ensemble curves of hip joint torques during stance phase, (EXT: ground reaction torque; GTT: gravitational torque; MDT: motion dependent torque; MST: muscle torque; NET: net joint torque). (B) The mean and standard deviation (error bars) of EXT, GTT, MDT and MST at the hip joint during stance 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 $10.0 \times 2.5 \times 2.0$ 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.

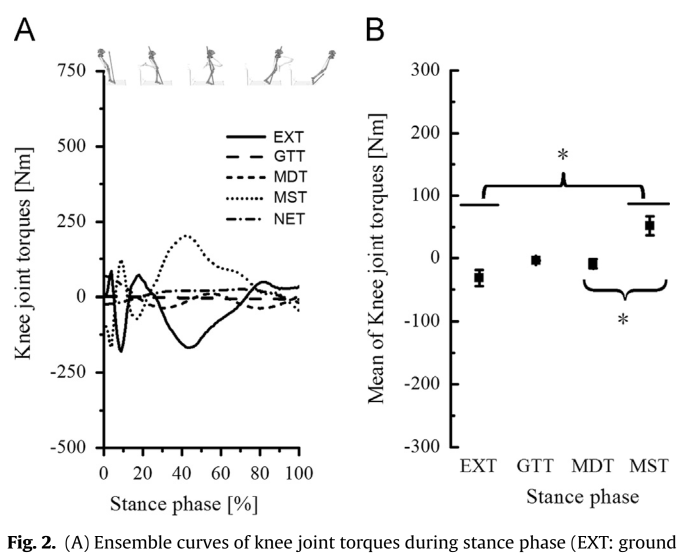

Fig. 2. (A) Ensemble curves of knee joint torques during stance phase (EXT: ground reaction torque; GTT: gravitational torque; MDT: motion-dependent torque; MST: muscle torque; NET: net joint torque). (B) The mean and standard deviation (error bars) of EXT, GTT, MDT and MST in the knee joint during stance 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.)

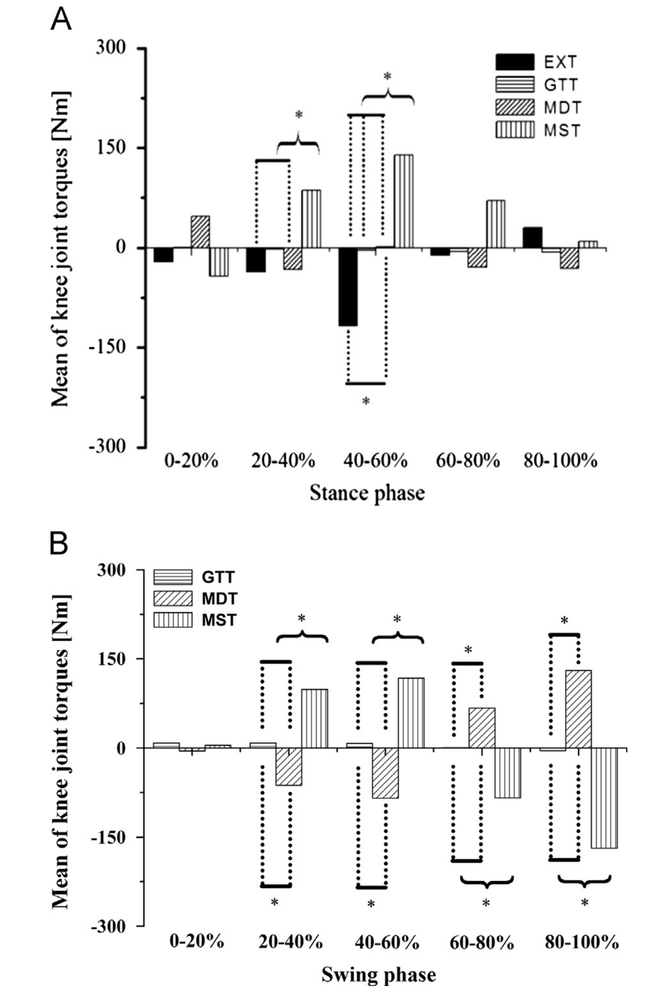

Fig. 3. (A) The mean of EXT, GTT, MDT and MST in the knee joint in each quintile during stance phase. * Indicates a statistically significant difference of knee joint torques in each quintile ($P<0.0001$). (B) The each quintile mean of GTT, MDT and MST of knee joint during swing phase. * Indicates a statistically significant difference in each quintile of knee joint torques ($P<0.0001$). (+: Extension torque, −: flexion torque.)

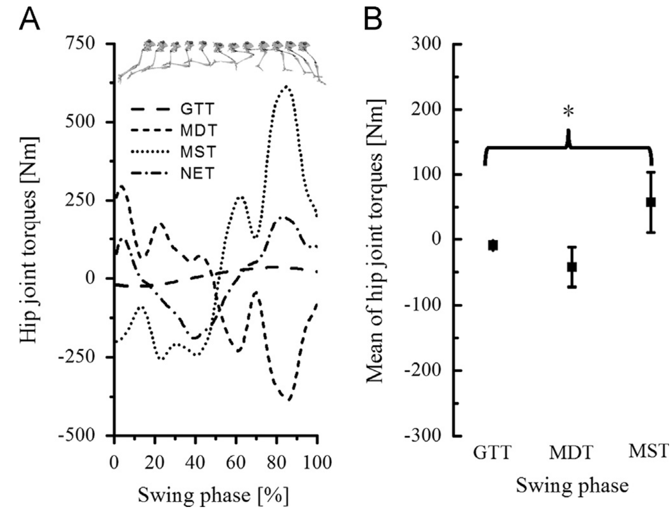

Fig. 4. (A) Ensemble curves of hip joint torques during swing phase (GTT: gravitational torque; MDT: motion-dependent torque; MST: muscle torque; NET: net joint torque). (B) The mean and standard deviation (error bars) of GTT, MDT and MST in the hip joint during swing phase. * Indicates a statistically significant difference between the mean of hip joint torques ($P<0.0001$) where MST is greater than GTT but both greater than MDT significantly. (+: Extension torque, −: flexion torque.)

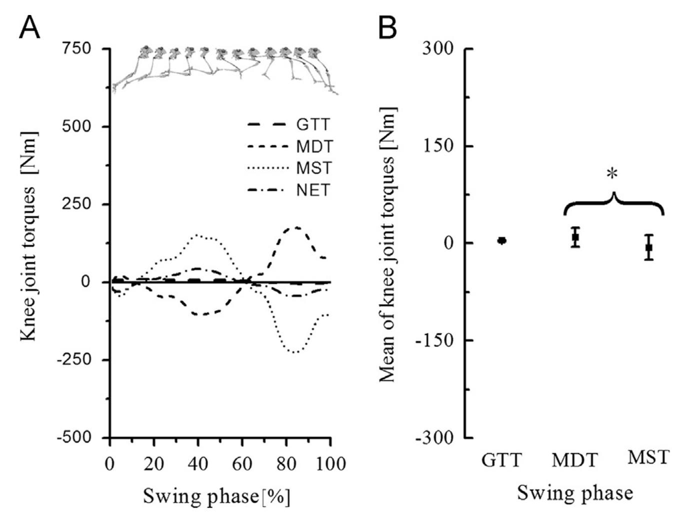

Fig. 5. (A) Ensemble curves of knee joint torques during swing phase (GTT: gravitational torque; MDT: motion-dependent torque; MST: muscle torque; NET: net joint torque). (B) The mean and standard deviation (error bars) of GTT, MDT and MST in the knee joint during swing phase. * Indicates a statistically significant difference between the mean of knee joint torques ($P<0.0001$) where MST is significantly less than MDT. (+: Extension torque, −: flexion torque.)

2.4. Statistical analyses

Average joint torque and their components over each quintile were evaluated by using two-factor (torque components × quintiles) analysis of variance (ANOVA) with repeated measures for the hip and knee joint. Stance and swing phases were analyzed separately. Pair-wise comparison post-hoc analysis was employed whenever significant interaction, or significant main effect among quintiles, or torque components were observed. Significance level for all statistical tests was set at $\alpha=0.05$.

The net summation of MST at hip, knee and ankle was defined as "support torque" (Winter, 2009) and the Pearson correlation coefficients between the mean support torque during stance phase and observed running speed were calculated.

3. Results

Mean running speed during data collection of all subjects was 9.7 ± 0.3 m/s.

3.1. Stance phase

3.1.1. Hip joint torque

At the hip joint, MST and EXT showed the greatest magnitude (Fig. 1A). Fig. 1B shows that the hip joint torque components, averaged over stance phase, were significantly different ($F_{3,\ 18}=100.15$, $P<0.0001$). EXT was significantly lesser than GTT and MDT but all three were significantly less than MST.

Detailed analysis revealed that different hip torque components experienced different changes across the quintiles during stance phase (significant torque component × quintile interaction, $F_{12,\ 72}=10.25$, $P<0.0001$, Table 1). MST was significantly greater than EXT, GTT and MDT except in the last quintile. EXT decreased significantly from first quintile (-85.24 ± 98.79 N m) to second quintile (-289.81 ± 106.75 N m). MST and MDT both showed profound changes in the last quintile, from 219.18 ± 196.67 N m and -102.07 ± 154.88 N m to -118.02 ± 176.93 N m and 192.86 ± 161.70 N m.

Positive correlation between the mean "support torque" and observed running speed ($r=0.89$, $P<0.05$).

Table 1
Mean hip joint EXT, GTT, MDT, MST, NET in each quintile during stance and swing phases (N m).

		0–20%	20–40%	40–60%	60–80%	80–100%
Stance phase	EXT	−85.24$^{\text{DEF}}$	−289.81$^{\text{G}}$	−151.16DEFG	−242.11$^{\text{FG}}$	−108.78$^{\text{DEFG}}$
	GTT	−17.43$^{\text{CDE}}$	−10.63$^{\text{CDE}}$	−3.04$^{\text{CDE}}$	6.24$^{\text{BCD}}$	15.37$^{\text{BCD}}$
	MDT	−58.22$^{\text{DEF}}$	−26.20$^{\text{DEF}}$	−222.24$^{\text{EFG}}$	−102.07$^{\text{DEFG}}$	192.86$^{\text{ABC}}$
	MST	223.48$^{\text{AB}}$	269.40$^{\text{A}}$	300.75$^{\text{A}}$	219.18$^{\text{AB}}$	−118.02$^{\text{DEFG}}$
	NET	65.809	−63.424	−80.202	−105.82	−10.347
Swing phase	GTT	22.58$^{\text{KL}}$	8.12$^{\text{KL}}$	−14.72$^{\text{L}}$	−31.57$^{\text{L}}$	−30.24$^{\text{L}}$
	MDT	178.75$^{\text{IJ}}$	108.43$^{\text{JK}}$	−60.65$^{\text{LM}}$	−175.99$^{\text{MN}}$	−261.88$^{\text{N}}$
	MST	−164.26$^{\text{MN}}$	−236.83$^{\text{N}}$	−33.07$^{\text{L}}$	283.37$^{\text{I}}$	438.87$^{\text{H}}$
	NET	37.068	−120.27	−108.44	75.811	146.75

Note: A, B, C, D, E, F, G, H, I, J, K, L, M and N denote different homogenous groups. Means which do not belong to the same group are statistically different.

3.1.2. Knee joint torque

EXT and MST were greater compared to MDT, GTT, and NET (Fig. 2A). The torque-time curves of EXT and MST showed multiple peaks and reached maximum values at about 45% of stance phase. Fig. 2B shows that, averaged over the entire stance phase, the knee joint torque components had different magnitudes ($F_{3,\ 18}=5.52$, $P<0.001$). Post-hoc analysis showed MST was significantly greater than EXT and MDT.

Significant differences between MST, EXT, and MDT mainly observed in the second and third quintiles during stance phase (significant torque component × quintile interaction, $F_{12,\ 72}=11.34$, $P<0.0001$, Fig. 3A). In the second quintile, MST was significantly greater than EXT and MDT. MST and EXT was significantly less than MDT in the third quintile.

3.2. Swing phase

3.2.1. Hip joint torque

MST and MDT showed the greatest torque and reached their maximum/minimum values in the second and fifth quintiles, respectively (Fig. 4A). Fig. 4(B) shows that average GTT, MDT and MST were significantly different over swing phase ($F_{2,\ 12}=49.92$, $P<0.0001$). MST was significantly greater than MDT and GTT, and GTT was significantly greater than MDT.

Different hip torque components experienced different changes across the quintiles during swing phase (significant torque component × quintile interaction, $F_{8,\ 48}=67.12$, $P<0.0001$, Table 1). MDT in the first and second quintiles was significantly greater than MDT in the other quintiles. MST in the fourth and fifth quintiles was significantly greater than MST in the other quintiles.

Fig. 6(A) shows the ensemble curves of components of motion-dependent torque (MDT) at the hip joint during swing phase. In the first as well as fourth and fifth quintiles, MDT at hip joint was mainly constituted of the torque due to leg angular acceleration (LAAT), thigh angular acceleration (TAAT) and hip linear acceleration (HLAT).

3.2.2. Knee joint torque

Fig. 5(A) presents the ensemble curves showing the torque-time history of the knee during swing phase. MDT and MST were greater in magnitude than GTT. Both MDT and MST had a peak in late swing phase (80–100%). MST changed from negative to positive values at about 10% of swing phase, and then changed from positive to negative values at about 60% and also reached a peak in late swing. However, the changes in MDT were opposite in sign to those of MST. Fig. 5(B) shows the values of the knee joint torque components over the whole swing phase. Significant differences were observed among the different torque components ($F_{2,\ 12}=7.35$, $P<0.0001$), with MDT being significantly greater than MST.

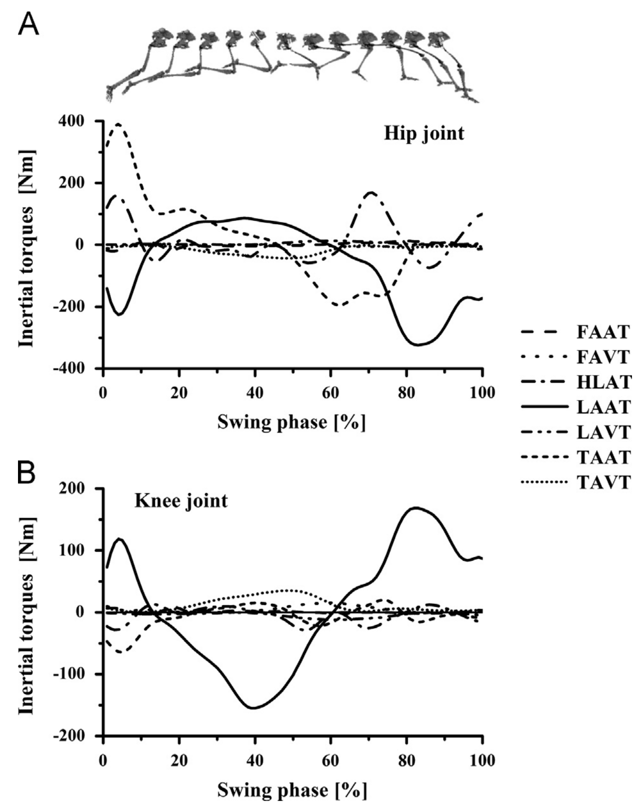

Fig. 6. Ensemble curves of components of motion-dependent (inertial) torques in the hip (A) and knee (B) joints during swing phase (FAAT: torque due to foot angular acceleration; FAVT: torque due to foot angular velocity; HLAT: torque due to hip linear acceleration; LAAT: torque due to leg angular acceleration; LAVT: torque due to leg angular velocity; TAAT: torque due to thigh angular acceleration; TAVT: torque due to thigh angular velocity; +: extension torque, −: flexion torque).

Further analysis reveals that different knee torque components experienced different changes across the five quintiles during swing phase (significant torque component × quintile interaction, $F_{8,\ 48}=82.68$, $P<0.0001$, Fig. 3B). There were significant differences among GTT, MDT and MST except in the first quintile during swing phase. Both MDT and MST in the fourth and fifth quintiles were significantly greater than those in the other quintiles. It indicates that MST functioned to extend knee, counteract the MDT, together with GTT in the second and third quintiles; meanwhile, MST acted to flex knee joint in the fourth and fifth quintile to counter balance the inertial effect of the MDT. In addition, MDT was mainly constituted of the torque due to leg angular acceleration (LAAT) across the five quintiles during the entire swing phase (Fig. 6B).

In addition, peak hip extensor torque and peak knee flexor torque, both occurred during the late part of the swing phase

(Figs. 4 and 5A), positively correlated with the observed running speed ($r=0.78$, $P<0.05$ at the hip and $r=0.73$, $P<0.05$ at the knee).

4. Discussion

We set out to study the function of muscle torque (MST) and its synergy with other torque components during elite sprint performance. Our results supported our hypothesis that the role of MST is very different in stance and swing phases. MST functioned mainly to counteract the torque due to ground reaction forces (EXT) during stance phase. This is evidenced by both hip (Fig. 1B) and knee (Fig. 2B) joint torque. However, MST acted principally to counteract the movement dependent torque (MDT) during swing phase for both hip (Fig. 4B) and knee (Fig. 5B) joint torque.

To account for the rapid change of the joint torques, and their components, we have divided the joint torque trajectories during stance and swing phases into quintiles. This method enabled us to further compare and contrast the mechanical actions during both stance and swing phases sprinting gait cycle. For example, MST at the hip joint was to counter EXT during the first quintile of the stance phase, but to work with the EXT during the fifth quintile of the stance phase. Its function at the first quintile was to help with the weight acceptance but to help preparing for flexing hip and extending knee in the fifth quintile. The quintiles helped us to interpret this and other observations with more details and statistical support. Provide us a tool to understand the details of the sprinting mechanics and functions of lower extremity muscles.

4.1. Stance phase

More detailed analysis considering each quintile revealed that the functional role of MST changes at different times and different joints during stance phases. Specifically, the main effect of MST at the hip joint was to provide an extension torque to counterbalance EXT, MDT, and GTT in the first quintile, mainly EXT in the second quintile, EXT and MDT in the third and fourth quintiles (Table 1). MST switched from an extension to a flexion torque in the fifth quintile to flex the hip joint, overcome MDT with the assistance of EXT that prepare the swing of the lower extremity. At the knee joint during stance phase, MST was relatively small in the first, fourth and fifth quintiles (Fig. 3A). The main functions of MST were (1) to counterbalance EXT and MDT in the second quintile and EXT and GTT in the third quintile to extend knee joint, and (2) to push the ground to create ground reaction force.

Mann and Sprague (1980) proposed that hip extensor torque dominated the initial stage of stance phase with concentric contraction. Muscle dominance then shifted to eccentric of the flexors for the rest of stance phase. Knee flexors were active up to mid-support, and then knee extensors took over through takeoff. Mann (1981) reported similar MST pattern during stance phase but added hip flexor-to-extensor, and knee extensor-to-flexor, sequences during swing. Our results showed that MST displayed a similar function at hip and knee joint during stance. However, hip extension torque switched to flexion torque later in stance phase (80–100%), which was a phenomenon also observed by Zernicke et al. (1991). These results indicated that MST at the hip joint no longer provided an impelling force for human movement in the last quintile of stance, but rather that MST with EXT acts at this time mainly to counterbalance MDT to flex the hip joint. This further implied that the role of MST might change from weight support during the first four quintiles to the preparation of swing during the last quintile.

On the other hand, the hip extension MST in this study during running switched to a flexion torque later than during walking. The discrepancy between our results and those of Mann and Sprague (1980) and Mann (1981) during stance phase was most likely because the running speed in our study was greater.

4.2. Swing phase

MST's functional role is simpler to describe during swing since there is no ground reaction force to be considered. Our data revealed that the largest muscle torque occurred at the end of the swing phase (Fig. 3B, Figs. 4 and 5, Table 1), where the largest hip extension and knee flexion MST happened at almost the same time. These results showed that the MST was used mainly to counterbalance the MDT during swing, which are complementary to the early results reported by (Phillips et al., 1983). They found that proximal thigh motion has a significant effect on the distal leg motion during running swing phase. Similarly, Putnam (1991) showed that MST and MDT played major roles in the proximal-to-distal sequential motion pattern during swing. In addition, interactions between muscular torque and motion dependent torque were also pronounced with increased speed of locomotion (Hoy and Zernicke, 1985; Winter, 2009).

From a movement control standpoint, we further observed that MST functioned as to counterbalance MDT to flex hip and extend knee at the first half of the swing phase, but to reverse to extend hip and flex knee during the second half of the swing phase (Figs. 4 and 5). Additionally, the major component of MDT in the first, fourth, and fifth quintiles was produced mainly by the acceleration of leg and thigh at the hip and the acceleration of leg at the knee (Fig. 6). These results partially support the conclusion proposed in a highly relevant study which found the initial and terminal stages of the swing need muscular torque to counteract the motion dependent torque and accelerate or decelerate the swinging limb (Zernicke and Schneider, 1993). In that study, however, the authors only pointed out the importance of motion dependent torque contributions during the swing phase of running and but failed to the details of MDT component among lower extremity segments. The results of the current study help us to further understand the origin of MDT, the interaction among MST, MDT and GTT, and their relevance to the movement control of swing limb during sprinting.

The positive correlation between the mean “support torque” at the stance phase and the observed running speed indicate the importance of extensor torque at hip and knee during stance phase. The positive correlation between the peak hip extensor (peak knee flexor) torque during the late swing phase and the observed running speed indicate the importance of extensor torque at the hip (flexor torque at the knee) during swing phase. Coaches and athletes can refer to these results to develop their training programs emphasizing not only extensor but also flexor muscles in accordance with characteristics of MST.

We have focused on muscle torque during sprinting stance and swing phases, and the relationship among MST, EXT and MDT. The muscle torque at the hip and knee joint were similar in magnitude and function to previous results for sprinting (Johnson and Buckley, 2001; Hunter et al., 2004). The value of our ISD analysis is in gaining insights into the lower extremity movement control during both the stance and swing phases. The ISD approach used in this study is an extension inverse dynamics, which is limited to calculate the net effect of muscle activity at a joint in terms of net muscle torque. For further understanding of individual muscle forces and their effects on movement and support force, forward dynamics solution of musculoskeletal model and dynamic optimization have to be conducted (Zajac et al., 2002; Anderson and Pandy, 2003). This is definitely the future research direction for studying sprinting. The statistical results presented in this paper have not been Bonferoni adjusted. We suggest the readers take this into consideration when interpreting the results of the project.

In conclusion, the ISD analysis helps us to understand muscle's role in movement control, its reaction to motion and interaction with the environment during sprinting. During the stance phase, MST functions mainly to push the ground to create ground reaction force, and to counteract each other for controlling the movement at both hip and knee joints. 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 hip and knee joints.

Conflict of interest statement

The authors have no financial or personal relationships that could inappropriately influence or bias this work.

Acknowledgments

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