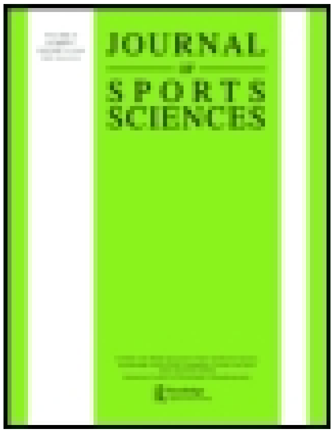

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Control of propulsion and body lift during the first two stances of sprint running: a simulation study

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Control of propulsion and body lift during the first two stances of sprint running: a simulation study

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Abstract

The aim of this study was to relate the contribution of lower limb joint moments and individual muscle forces to the body centre of mass (COM) vertical and horizontal acceleration during the initial two steps of sprint running. Start performance of seven well-trained sprinters was recorded using an optoelectronic motion analysis system and two force plates. Participant-specific torque-driven and muscle-driven simulations were conducted in OpenSim to quantify, respectively, the contributions of the individual joints and muscles to body propulsion and lift. The ankle is the major contributor to both actions during the first two stances, with an even larger contribution in the second compared to the first stance. Biarticular gastrocnemius is the main muscle contributor to propulsion in the second stance. The contribution of the hip and knee depends highly on the position of the athlete: During the first stance, where the athlete runs in a forward bending position, the knee contributes primarily to body lift and the hip contributes to propulsion and body lift. In conclusion, a small increase in ankle power generation seems to affect the body COM acceleration, whereas increases in hip and knee power generation tend to affect acceleration less.

Keywords: *sprint start, biomechanics, simulation, sprint performance*

Introduction

Sprinting performance is determined by the athletes' ability to generate maximal forward acceleration, to attain high velocity and to maintain this velocity as long as possible during the remainder of the run (Ross, Leveritt, & Riek, 2001).

Specific technical skills are needed to address the biomechanical demands of the acceleration phase (Delecluse, 1997): Previous research showed that during acceleration, powerful hip extensor action by hamstrings and gluteus maximus induces a large forward impulse and therefore propels the athlete forward. This is referred to as the "hip extensor theory" (Kunz & Kaufmann, 1981; Mann & Herman, 1985). However, the hip extensors only determine forward acceleration during the first-third of the stance, when minimal forward acceleration is produced. During the following two-thirds, the hip flexors generate high acceleration, assisted by the knee extensor moment for maintaining the height of the centre of mass (COM) and the ankle plantar flexor moment that prevents collapse of the shank (Hunter, Marshall, & McNair, 2004; Johnson & Buckley, 2001).

However, the biomechanical demands of the first stances after block clearance are very different compared to the other stances during acceleration. The sprinter aims to generate maximal forward acceleration during the transition from start block into sprint running (Bezodis, Salo, & Trewartha, 2010; Golden, Pavol, & Hoffman, 2009). Simultaneously, the athlete needs to generate sufficient upward acceleration to erect from a flexed position in the start blocks to a more extended position (Debaere, Delecluse, Aerenhouts, Hagman, & Jonkers, 2013). Specific technical skills are therefore needed to successfully achieve this transition. At joint level, the hip extensors generate most power before and during initial contact of the first stance, assisted first by the knee extensors and only minimally by the ankle plantar flexors. From the second stance onwards, the hip remains the largest power generator, assisted by the ankle plantar flexors and with only minimal contribution of the knee extensors (Charalambous, Irwin, Bezodis, & Kerwin, 2012; Debaere et al., 2013). electromyography (EMG) patterns confirm biceps femoris activity before and at the beginning of stance

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whereas they confirm rectus femoris, vasti lateralis and medialis, gastrocnemius and soleus activity during the entire stance (Guissard & Duchateau, 1990).

Although informative on the timing and magnitude of the different lower limb joint moments and muscle action, these descriptive studies fail to relate the lower limb joint moments and muscle activity, to forward and upward acceleration of the body COM. Based on the described differences in power generation during first and second stance (Debaere et al., 2013), we hypothesise that the specific contribution of the ankle and knee joint can be causally related to specific demands in accelerating the COM vertically and horizontally during these initial two steps of sprint running. This study used torque-driven forward simulations to quantify the separate contribution of the ankle and knee joint moments to the forward and upward acceleration of the COM. Next, muscle-driven forward simulations were used to extend these insights to the contribution of individual lower leg muscle and more specific bi-articular muscles, to the control of the COM during initial sprint running.

Methods

Participants

Seven well-trained sprinters (2 men and 5 women) gave their written consent to participate in the study. Their age, body mass and height are presented in Table I. Personal best times over 100 m ranged between 11.10 s and 11.77 s in men and between 12.05 s and 12.36 s in women (Table I). Well-trained sprinters were selected as they can be expected to have developed the most effective technical skills to handle this transition. This study conforms to the recommendations of the Declaration of Helsinki and had been approved by the local Ethics Committee.

Procedures

Testing took place at the beginning of the summer season in a gymnastic hall with a tartan track surface. After an individualised warm-up, all sprinters completed three maximal effort 10 m sprints, with complete recovery between each trial. Each participant wore their own spiked shoes and adjusted the start blocks to the position used during competition. Starting commands were identical to those used in competition.

Data collection

Optoelectronic motion capture system. Kinematics were measured using three-dimensional (3D) motion analysis (Vicon, Oxford Metrics, UK). Data were collected using twelve MX3 cameras (sampling at 250 Hz) positioned to collect data in the starting block and during the first two steps, covering a total measurement volume of 5 m (length) × 2 m (width) × 2 m (height) (Figure 1). A full body marker placement protocol was used consisting of 74 spherical reflective markers, with 32 belonging to 8 technical clusters on the thighs and shanks (Figure 2). After the static trial in T-position (Figure 2), 8 medial markers were removed for the sprinting trials.

Force platforms. Ground reaction forces were measured during the first two contacts using two Kistler force plates (1000 Hz) embedded in the track.

Both systems were recorded synchronously in the Vicon system.

Data processing

Musculoskeletal model description and scaling. After initial marker labelling in Nexus (Vicon, Oxford Metrics, UK), a generic musculoskeletal model with 14 segments (head-trunk (HT), pelvis and bilateral upper arm, lower arm, hand, femur, tibia and foot) and 26 degrees of freedom with a 92 muscle-tendon actuators model (Hamner, Seth, & Delp, 2010) was used. The standard Thelen2003 muscle model implemented in OpenSim 1.9.1 was used. This model uses a standard equilibrium muscle model based on the Hill model. The muscle–tendon complex consists of

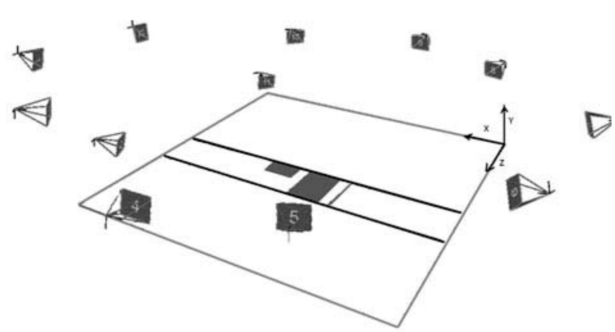

Figure 1. Motion capture set-up.

Table I. Characteristics of the sprinters (mean ± *s*): age in years, body mass in kilogram, body height in metre and 100 m personal best (PB 100 m) in seconds.

	Age (years)	Body mass (kg)	Body height (m)	PB 100 m (s)
Characteristics of the sprinters (mean ± *s*)	19.75 ± 3.01	59.71 ± 9.93	1.71 ± 0.12	11.97 ± 0.42

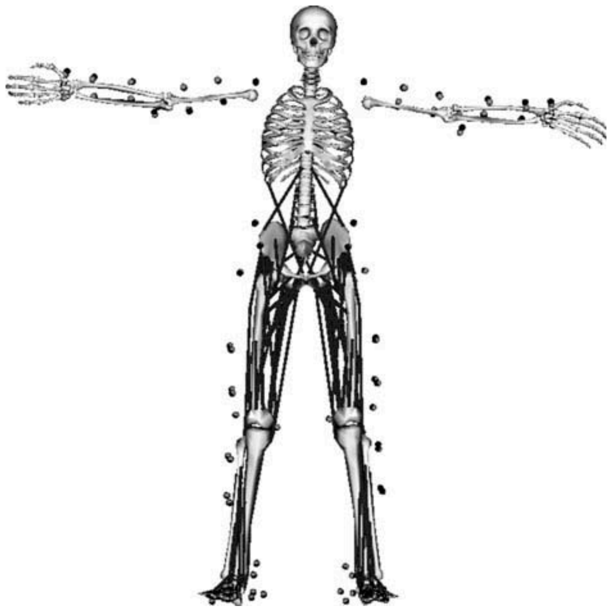

Figure 2. Static trial with body labelled with 74 passive reflective markers: on the processus spinosus of C7, on the lateral aspect of the acromion bilaterally, lateral and medial elbow, lateral and medial wrist, on the processus spinosus of L3, spina iliaca anterior superior, spina iliaca anterior inferior, greater trochanter, lateral and medial knee, lateral and medial ankle, heel (2), lateral, medial and middle forefoot, and toe and including 8 technical clusters: mid-humeri, mid-radius, mid-femur, and mid-shank. For the head-trunk, the lumbar spine presented three degrees of freedom with respect to the pelvis segment describing flexion/extension, bending and rotation; the shoulder presented three degrees of freedom of the upper arm with respect to the head-trunk (flexion/extension, abduction/adduction and exo-/endorotation); the elbow contained two degrees of freedom between upper and lower arm (flexion/extension and pronation/supination); the hip was modelled to represent three degrees of freedom (flexion/extension, abduction/adduction and exo-/endorotation); the knee was modelled as one degree of freedom between thigh and shank representing flexion/extension; the ankle was modelled as one degree of freedom representing plantar/dorsiflexion; the pelvis movement with respect to the ground is represented with three rotational (tilt, list and rotation) and three translational degrees of freedom (defined according to Hamner et al., 2010).

three components: a contractile element (CE), a parallel element (PE), and a series element (SE). The muscle force generated is a function of three factors: the activation value (a), the normalised length of the muscle unit, and the normalised velocity of the muscle unit. For a full description of the muscle model the reader is referred to http://simtk-confluence.stanford.edu:8080/display/OpenSim/Thelen+2003+Muscle+Model.

The generic model was then scaled to accommodate the individual anthropometry based on marker positions obtained during a static trial (Delp et al., 2007). For the head-trunk, the lumbar spine presented three degrees of freedom with respect to the pelvis segment describing flexion/extension, bending and rotation; the shoulder presented three degrees of freedom of the upper arm with respect to the head-trunk (flexion/extension, abduction/adduction and exo-/endorotation); the elbow contained two degrees of freedom between upper and lower arm (flexion/extension and pronation/supination); the hip was modelled to represent three degrees of freedom (flexion/extension, abduction/adduction and exo-/endorotation); the knee was modelled as one degree of freedom between thigh and shank representing flexion/extension; the ankle was modelled as one degree of freedom representing plantar/dorsiflexion; The pelvis movement with respect to the ground is represented with three rotational (tilt, list and rotation) and three translational degrees of freedom (Hamner et al., 2010).

Reserve actuators, i.e., instantaneous torque generators acting at the joints, were implemented to assure stable tracking of the simulation kinematics in case insufficient instantaneous muscle force generation was encountered during the muscle-driven simulations (see Supplemental data).

Inverse kinematics and dynamics. Based on the 3D marker trajectories during the running trial, an inverse kinematics procedure was conducted to calculate the relevant joint angles. An inverse dynamic procedure calculated the net reaction forces and moments at each of the joints (Delp et al., 2007). Details are added in Supplemental data.

Velocity of the COM in the forward, upward and medio-lateral direction was calculated using a multibody kinematic evaluation that calculates the body COM based on the location of the COM of individual segments. The inertial and dynamic parameters of each body segment in the model are scaled based on relative distances between pairs of markers obtained from a motion capture system and the corresponding virtual marker locations in the model are implemented in OpenSim (Delp et al., 2007), whereas individual body segment masses are scaled with respect to the total body mass. A more detailed description of the dedicated processing workflow can be found in the study of Debaere et al. (2013).

Generation of moment- and muscle-driven simulations. We generated torque-driven simulations to quantify the contributions of the individual joint torques to the forward and upward acceleration of the body COM during first and second stance after block clearance. These simulations assume ideal torque generators at each DOF of the model that can instantaneously change their torque production to track the experimentally measured, participant-specific kinematics. Similarly, by means of muscle-driven simulations, the contribution of individual muscles to the forward and upward acceleration of the body COM was calculated.

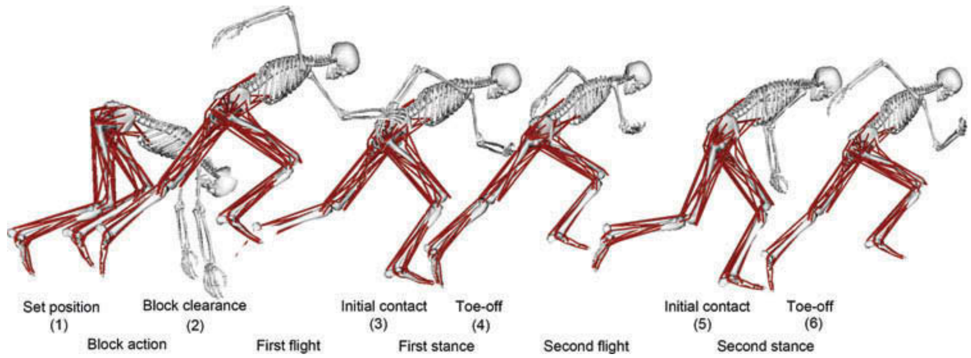

Figure 3. Timing of relevant events. Block clearance is presented as the moment from first action after gunshot, i.e., set position (1) until the foot has left the rear or front block (2). The contact phase is defined as the instant of touchdown of the foot, i.e., initial contact first (3) and second stance (5), to the instant the same foot leaves the ground, i.e., take-off first (4), and the flight phase is defined as the instant of take-off of one foot to the instant of touchdown of the ipsilateral foot. Touchdown was estimated as the first frame where the athlete's foot contacted the track, whereas take-off was indicated as the first instant where the foot has fully left the ground or starting block.

Both torque and muscle-driven simulations were generated using the standard workflow in OpenSim. Simulations were generated from the instant the athlete's foot made contact with the track (touchdown) to the instant the same foot leaves the ground (take-off) (Figure 3). In a first analysis step, a residual reduction algorithm (RRA) was used to reduce the dynamic inconsistencies between the model kinematics and the measured ground reaction forces (Thelen & Anderson, 2006). Thereafter, computed muscle control (CMC) was used to compute a set of joint torques or a set of muscle excitations for the torque and muscle-driven simulations, respectively, allowing the simulation to track the sprinting kinematics (Thelen & Anderson, 2006). Finally, a perturbation analysis computed the contribution of a specific joint torque (for the torque-driven simulations), or specific muscle force (for muscle-driven simulations) to the horizontal and vertical acceleration of the COM. We increased the torque/force of the individual actuators with 1 N/1 Nm after which the equations of motion were integrated forward over a 0.03 s, using a 0.01 s time step for the integration, after which the induced acceleration to the body COM was calculated. The cumulative contribution of the individual actuators to horizontal and vertical acceleration was calculated by summing the induced acceleration ($m \cdot s^{-2}$) over the duration of the first (0.195 s ± 0.017) and second stance (0.172 s ± 0.014). The net induced horizontal and vertical acceleration during each stance was then calculated by summing the cumulative acceleration contribution of all actuators. The contributions to horizontal acceleration (propulsion) and vertical acceleration (body lift) were then calculated as a percentage contribution of the cumulative acceleration of the actuators/muscles with respect to the net induced acceleration.

After rank-ordering of the induced accelerations, only the joints and muscles contributing more than 85% of the net induced horizontal and vertical acceleration in each of the stances were considered for further analysis. For practical reasons only joint and muscle contributions exceeding 5% of the induced horizontal and vertical acceleration were reported. Furthermore, we analysed the number of athletes in which the contribution of a specific muscle is confirmed, as a stability measure of the result given the observed variability in the kinematics and kinetics. Only the contribution of the joints and muscles generating more than 85% of the net induced horizontal and vertical acceleration in each of the stances were considered for further analysis.

Simulation performance level. The mean value ± *s* of the tracking, i.e., difference between RRA and CMC, of the muscle actuated simulation is presented in Table I. The mean value ± *s* of the moments produced by the reserve actuators during muscle-driven simulation where necessary can be found in Table 1S. Details on simulation performance are added in Supplemental data.

Results

Based on the kinematics analysis of the COM acceleration, all athletes generated higher maximal forward acceleration during the first (0.36 $m \cdot s^{-2}$ ± 0.05) compared to the second stance(0.23 $m\ s^{-2}$ ± 0.04), whereas upward acceleration differed minimally: 0.28 $m \cdot s^{-2}$ ± 0.08 during the first stance and 0.25 $m \cdot s^{-2}$ ± 0.05 during the second stance.

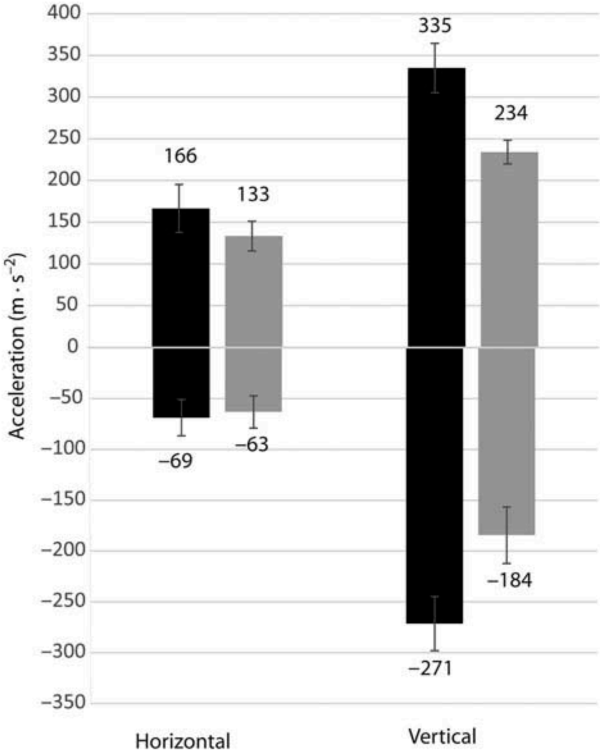

Figure 4. Horizontal and vertical net induced acceleration and deceleration of the first and second stance.

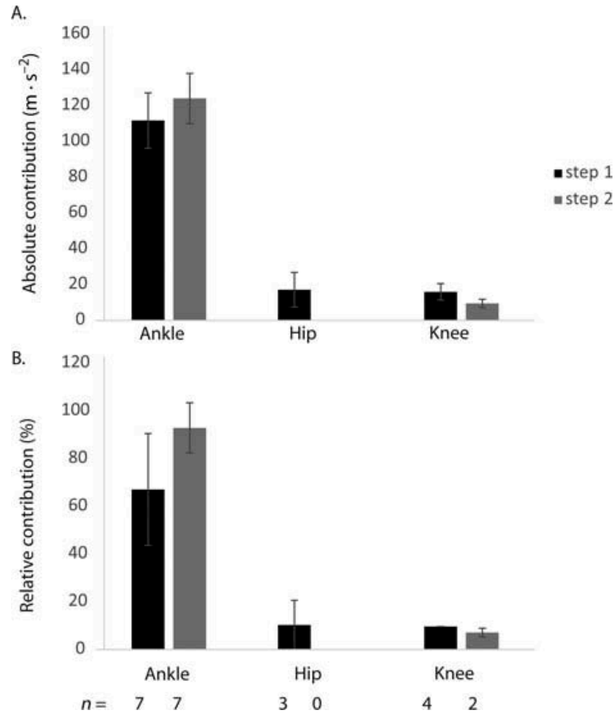

Figure 5. Absolute (top) and relative (bottom) contribution to the COM horizontal acceleration, expressed in $m \cdot s^{-2}$ of the lower limb joints during the first (dark grey) and the second (light grey) stance after block clearance.

Net induced acceleration

Joint moments induced a higher net acceleration in the first (501.4 $m \cdot s^{-2} \pm 164.4$) compared to the second stance (367.7 $m \cdot s^{-2} \pm 36.7$). During the first stance, they mainly contribute to upward acceleration (body lift) (66.8%), compared to 33.2% contribution to forward acceleration (propulsion). During the second stance, this contribution to body lift is only slightly reduced (63.7%) (Figure 4).

Contribution to COM acceleration–deceleration (propulsion-breaking)

Propulsion was generated during the majority of stance. The ankle joint of the stance leg contributed most to COM propulsion in all athletes during first (67.1%) and second stance (92.9%). The auxiliary role of knee and hip joint of the stance leg changed between first and second stance: A hip joint moment contribution to propulsion is only presented during the first stance (10.3%). The knee joint moment contribution, however, decreased slightly from 9.6% during the first stance to 7.1% during the second stance (Figure 5).

At muscular level, the ankle plantar flexors of the stance leg, i.e., gastrocnemius (25.3% during the first and 28.8% during the second stance) and soleus (31.7% during the first and 26.7% during the second stance), contributed most to propulsion. Additionally hip extensors of the stance leg, more specific biceps femoris (5.4%) and gluteus medius (5.6%), and knee extensor muscles of the stance leg, i.e., vasti (11.4%) and rectus femoris (6.8%), contributed to propulsion during the first stance (Figure 6). The hip and knee extensor contribution decreased below the threshold of 5% during the second stance.

Contribution to COM upwards acceleration (body lift)

All three lower limb joints of the stance leg contributed to upward acceleration during the first stance (hip: 12.3%, knee: 38.1% and ankle: 49.6%). During the second stance, however, only ankle and knee joints contributed to body lift (resp. 76.2% and 23.8%) (Figure 7). This was confirmed in all athletes' data.

Ankle plantar flexors of the stance leg, i.e., soleus (resp. 35.9% and 28.0% in first and second stance) and gastrocnemius (resp. 19.5% and 24.2%) contribute most to body lift in all athletes. Knee extensors of the stance leg, vasti (resp. 29.3% and 19.3%) and rectus femoris (resp. 15.2% and 10.0%), contribute less during the second stance. A small contribution of the hip extensors of the stance leg, i.e., biceps femoris (5.1%), is found during the second stance only (Figure 8).

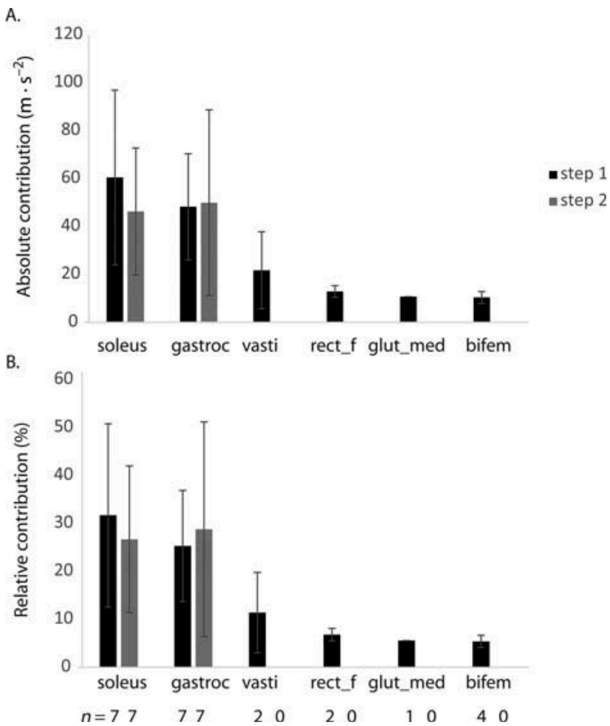

Figure 6. Absolute (top) and relative (bottom) contribution to the COM horizontal acceleration, expressed in $m \cdot s^{-2}$ of the lower limb muscles during the first (dark grey) and the second (light grey) stance after block clearance.

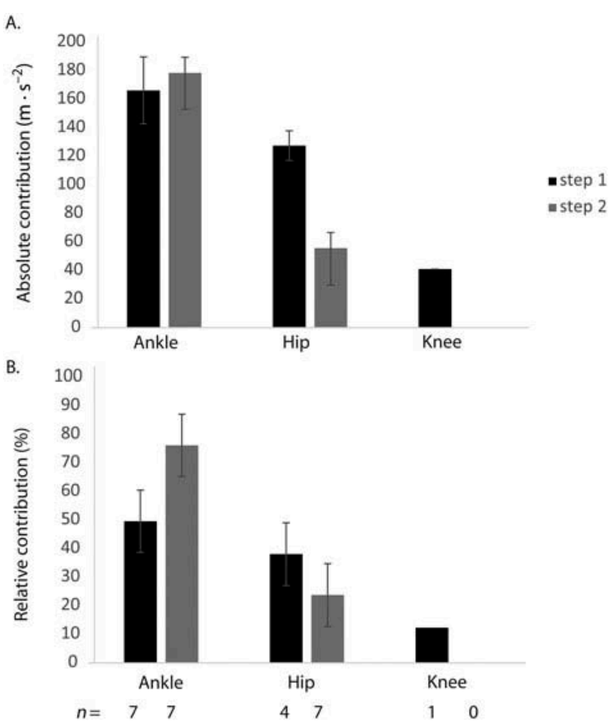

Figure 7. Absolute (top) and relative (bottom) contribution to the COM vertical acceleration, expressed in $m \cdot s^{-2}$ of the lower limb joints during the first (dark grey) and the second (light grey) stance after block clearance.

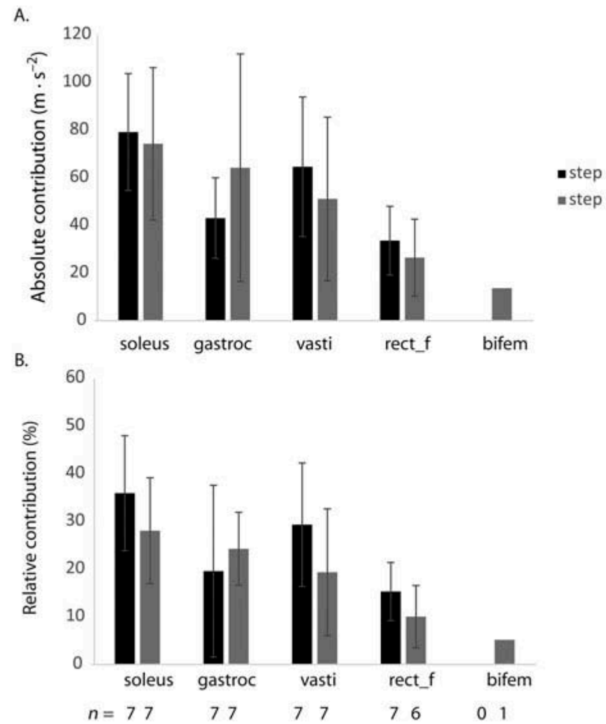

Figure 8. Absolute (top) and relative (bottom) contribution to the COM vertical acceleration, expressed in $m \cdot s^{-2}$ of the lower limb muscles during the first (dark grey) and the second (light grey) stance after block clearance.

Discussion

The aim of this study was to relate the contribution of lower limb joints to the specific biomechanical demands underlying the body COM propulsion and body lift during the initial two steps of sprint running. To further elucidate the role of biarticular muscles, the analysis was extended to include individual muscle contributions.

Several papers already documented the role of individual muscles in COM control during walking and running (Hamner et al., 2010; Jansen et al., 2012; Liu, Anderson, Pandy, & Delp, 2006; Liu, Anderson, Schwartz, & Delp, 2008; Neptune, Kautz, & Zajac, 2001; Neptune, Zajac, & Kautz, 2004). In sprinting, only descriptive studies documenting kinematics, kinetics and EMG are available (Bezodis, Kerwin, & Salo, 2008; Charalambous et al., 2012; Debaere et al., 2013; Guissard, Duchateau, & Hainaut, 1992; Johnson & Buckley, 2001; Kugler & Janshen, 2010; Morin, Edouard, & Samozino, 2011; Slawinski, Bonnefoy, Leveque, et al., 2010; Slawinski, Bonnefoy, Ontanon, et al., 2010). From these studies, it is known that the first and second stance imposes specific biomechanical demands that require technical skills favouring knee above ankle action during the first stance

(Charalambous et al., 2012; Debaere et al., 2013; Jacobs & van Ingen Schenau, 1992). However, so far, it remained unclear if this is mediated by specific contribution of the lower limb joints and muscle groups to body propulsion and lift.

The findings in the current study clarify that during the first stance of sprint running, joint and muscle action will merely contribute to body lift as is reflected in the high percentage contribution to the net induced vertical acceleration. Only, during the second stance, propulsion becomes more important (Figure 4). Therefore, the positional changes between the first and second stance, i.e., the change from a bended forward trunk position into a more-upright but still forward leaning position require the athlete to not only invest in maximising forward velocity, but also to invest in upward velocity.

The ankle contributes most to propulsion and body lift. Its role in generating forward and upward acceleration even increases from the first to second stance as reflected in the percentage contribution (Figures 5 and 7). This is confirmed at muscle level with ankle plantar flexors soleus and gastrocnemius contributing most to forward and upward acceleration (Figures 6 and 8). This finding relates to the advantage of the flexed positioning of the athlete during the first step in maximising the effect of the plantar flexor action: the anterior position of the COM to the point of foot contact combined with the forceful contraction of the plantar flexors is the main mechanism to advance and lift the athlete during first and second stance (Debaere et al., 2013; Hunter, Marshall, & McNair, 2005; Kugler & Janshen, 2010; Morin et al., 2011).

The specific role of the knee during the first stance was already described in previous studies (Charalambous et al., 2012; Debaere et al., 2013). The current results further specify its main role to accelerate the COM upwards, therefore providing body lift (Figures 5 and 7). Indeed, the knee joint moment contribution to propulsion is smaller and is limited to the end of both first and second stance (see Supplemental data). The specific timing of this contribution is in agreement with Jacobs and van Ingen Schenau (1992) and Debaere et al. (2013) who described postponed lower limb extension to support performance. Furthermore and in agreement with our previous work (Debaere, Delecluse, Aerenhouts, Hagman, & Jonkers, 2012; Debaere et al., 2013), knee contribution to forward and upward acceleration decreases substantially during second stance. Knee action during the first stance is therefore mainly directed to facilitate body lift.

The hip joint moment and hip extensor muscles contribute only minimally to propulsion and body lift during the first stance: more specifically only a limited contribution to body lift is seen during the first part of stance. The absence of contribution to propulsion contradicts the "hip extension theory," (Hunter et al., 2004) which states that the hip joint and hip extensor muscles are the major determinants of propulsion during the secondary acceleration phase where the sprinter gradually raises his trunk in order to evolve into a fully upright running position (Figure 2S, Supplemental data).

Focusing on the joint moment contributions to propulsion and body lift, we see some apparent contradictions with the previously reported joint moments during the first stance: Despite the relatively lower joint moments at the ankle, the joint is able to efficiently contribute to propulsion and body lift. The increased knee moment during first stance relates to the specific contribution to body lift. During the second stance, the knee and ankle joint moments and contributions to body lift and propulsion are however more in accordance, due to the positional changes. Although large power generation is present at the hip during first and second stance, this only contributes minimally to propulsion and body lift during the first and second stance.

At muscle level, our analysis shows a larger contribution of the biarticular gastrocnemius to body COM acceleration during the second compared to the first stance, with the gastrocnemius becoming the most important contributor to propulsion (Figures 6 and 8). This finding agrees with previous work focusing on the role of biarticular muscles in intersegmental power transfer: The biarticular action allows the transfer of power produced by monoarticular knee muscles to the ankle, therefore supporting proximal-to-distal muscle action (Bezodis et al., 2008).

Specific limitations of the applied methodology need to be discussed as they may influence the interpretation of the results. The findings in this paper are based on seven well-trained sprinters. Carefulness with generalisation of these results to sprinters of different performance level or to phases outside the phase under examination is appropriate (Bezodis et al., 2008; Charalambous et al., 2012; Debaere et al., 2012; Jacobs & van Ingen Schenau, 1992; Johnson & Buckley, 2001). The soleus is pointed out as the muscle that contributes most to progression as well as body lift. This result does, however, not make any assumption of the constitution, fast or slow twitch fibres, of the muscle. The model sees muscles like some sort of string that lengthens or shortens. The soleus spans the ankle joint. Therefore, the ankle will extend during the contraction of the muscle. In addition, the gastrocnemius is a biarticular muscle that not only affects ankle plantar flexion, but also affects knee flexion. During stance, the sprinter only wants to extend his lower limb. Therefore, we can assume that the soleus will extend the ankle joint, whereas the gastrocnemius will, besides extending the ankle joint, also transport energy from the knee joint to the ankle joint (Bezodis et al., 2008). Furthermore, the use of reserve actuators to assure stability of the muscle-driven simulation will result in an instantaneous underestimation of the muscle contribution. However, the engagement of the reserve actuators was within acceptable limits (see Supplemental data). Although their contribution is limited, the muscle contribution at the hip may be underestimated as the hip joint moment is now partially accounted for by the reserve actuators. However, the limited contribution of the hip moment in the joint-driven simulation confirms indirectly the limited role of the hip extensor muscles.

Conclusion

This study is the first study to relate the specific joint and muscle contribution to the horizontal acceleration (propulsion) and vertical acceleration (body lift) of the body COM during the initial two steps after block clearance. Torque-driven simulations identify the ankle joint as the major contributor to propulsion and body lift. The contribution of the hip and knee joint depends highly on the position of the athlete. During first stance where the sprinter is in a flexed position, the knee contributes to upward acceleration, lifting the athlete from the bended starting position. Likewise, the hip contributes to propulsion as well as body lift at the beginning of the first stance. However, during second stance, where the sprinter is in a more erected position, the contributions of hip and knee joints to upward acceleration are greatly reduced. Furthermore, the muscle-driven simulations confirm the role of the biarticular gastrocnemius from the second stance onwards.

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Supplemental data

Supplemental data for this article can be accessed here.

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