

SHORT COMMUNICATION

Lower leg morphology in runners: forefoot strikers have longer heels but not bigger muscles than rearfoot strikers

L. S. Wessbecher¹ and A. N. Ahn^{2,*}**ABSTRACT**

Foot strike pattern used during running may relate to lower leg morphology. We tested the hypotheses that forefoot strike (FFS) runners have longer plantarflexor moment arms (r) and larger plantarflexor muscles than rearfoot strike (RFS) runners. FFS runners had 17% longer r than RFS runners, but all runners had similarly sized medial and lateral gastrocnemius (MG and LG) muscles. Because muscle size also depends on activation pattern (Ahn et al., 2011), we compared MG:LG activation bias during walking in 24 runners and 23 sedentary subjects. Half of all subjects activated their MG and LG muscles equally ('unbiased') while walking, while the other half activated their MG more strongly than their LG muscles ('MG-biased'). Unbiased sedentary subjects had 16–23% smaller MG muscles compared with MG-biased sedentary subjects, unbiased runners and MG-biased runners. Muscle contraction dynamics during FFS running may balance the effects of longer plantarflexor moment arms in determining MG and LG muscle size.

KEY WORDS: Locomotion, Runners, Gastrocnemius, Foot strike, Plantarflexor

INTRODUCTION

Runners land with two possible biomechanical patterns. Those who rearfoot strike (RFS) land on their heels and typically generate a relatively high impact force (Lieberman et al., 2010). RFS runners land dorsiflexed with flexed ankles, then plantarflex (or extend) onto their midfeet (Ahn et al., 2014). Alternatively, forefoot strike (FFS) and midfoot strike (MFS) runners typically land on their fore- or midfoot to cushion the impact (Cavanagh and LaFortune, 1980; Lieberman et al., 2010). FFS and MFS patterns are kinematically and neurally grouped as 'FFS' because these runners land plantarflexed with earlier and longer activation of the gastrocnemii muscles (Ahn et al., 2014). The plantarflexor moment arm (r) inversely relates to the magnitude of force generated by the plantarflexor muscles to produce a moment, or rotating force, about the ankle joint. During a FFS, for example, isometric or lengthening contractions would generate relatively high plantarflexor forces due to the force–velocity relationship of muscle (Farris and Sawicki, 2012; Hill, 1938). Energetically, a longer r reduces elastic energy storage during running (Scholz et al., 2008; Raichlen et al., 2011). However, biomechanically, a longer r could provide a mechanical advantage by decreasing the plantarflexor force necessary to FFS. Since

runners with a longer r require less muscle force to FFS, we predicted that runners who FFS will have longer r than those who RFS.

In addition to r , thickness of the triceps surae muscles varies among individuals due to training type or differences in muscle activation patterns in sedentary individuals (Abe et al., 2000; Komi, 1986; Ahn et al., 2011; Baxter and Piazza, 2013). As a group, sedentary individuals have the same triceps surae muscle thickness as distance runners (Abe et al., 2000). In healthy young men, plantarflexor moment arm correlates with plantarflexor muscle volume and torque (Baxter and Piazza, 2013). However, sedentary individuals divide into two sub-groups depending on their muscle activation pattern during walking: 'MG-biased' individuals activate their medial gastrocnemius muscle (MG) more strongly than their lateral gastrocnemius (LG) and 'unbiased' individuals activate both MG and LG muscles equally (Ahn et al., 2011). MG-biased individuals have larger MG muscles than unbiased individuals (Ahn et al., 2011). As sedentary subjects walk faster, activation of their MG and LG muscles become less biased (Ahn et al., 2011). Since fast walking uses unbiased muscle activation, running likely also requires an unbiased recruitment of triceps surae muscles. Although the amplitudes of activity may be similar between the MG and LG muscles during running, its timing depends on the foot strike pattern (Ahn et al., 2014). FFS landing with a plantarflexed ankle requires earlier activation of the MG and LG muscles than the RFS landing with a heel strike (Ahn et al., 2014). In FFS running, the earlier MG activation and initial dorsiflexion likely results in an isometric or lengthening contraction of the plantarflexor muscles at the beginning of stance (Shin et al., 2009; Farris and Sawicki, 2012; Ahn et al., 2014). Since isometric and lengthening contractions of muscle result in greater hypertrophy (Higbie et al., 1996), we expected that runners who FFS will have larger plantarflexor muscles than those who RFS (Lieberman, 2012).

To examine the relationship between lower leg morphology and foot strike pattern, we measured plantarflexor moment arms (r) and gastrocnemii muscle thickness in runners. (Ahn et al., 2011). We hypothesized that plantarflexor muscles and r will be greater in runners who FFS than in those who RFS.

MATERIALS AND METHODS**Subjects**

The subjects consisted of 41 runners (23 female, 18 male; age, 27.5±1.7; BMI: 21.9±0.5 kg m⁻²; means±s.d.) and 23 sedentary individuals (12 female, 11 male; age, 23.3±1.7 years; BMI: 21.5±0.4 kg m⁻²). Runners ran between 7 and 85 miles per week (27.6±3.1 miles) and categorized themselves as either recreational ($N=25$) or highly trained who competed regularly ($N=16$). Of the 41 runners, 14 consistently used a FFS pattern when barefoot and shod, 19 'shifters' used a FFS when barefoot and shifted to a RFS when shod, and 8 runners consistently used a RFS pattern when barefoot and shod (Fig. 1).

¹Keck Science Department, Scripps College, Claremont, CA 91711, USA.

²Department of Biology, Harvey Mudd College, Claremont, CA 91711, USA.

*Author for correspondence (aahn@hmc.edu)

 L.S.W., 0000-0003-4980-0706; A.N.A., 0000-0001-9628-5335

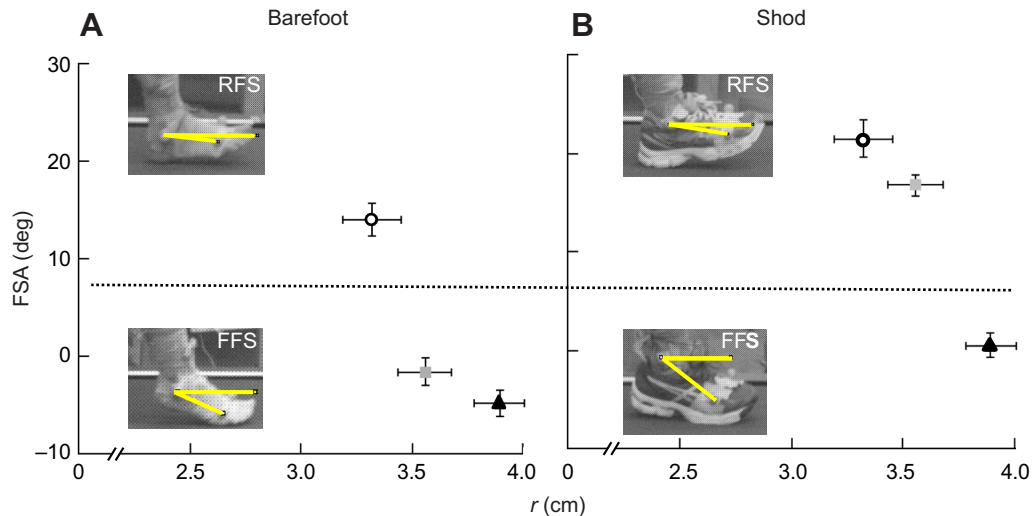


Fig. 1. Runners with longer plantarflexor moment arms (r) tend to forefoot strike. Foot strike angle (FSA) in (A) barefoot and (B) shod runners as a function of r . Forefoot strike (FFS) runners ($N=14$) land with FSA <8 deg (below dotted horizontal line). Rearfoot strike (RFS) runners ($N=8$) land with FSA >8 deg. Shifters (gray squares; $N=19$) FFS when barefoot (A) and RFS when shod (B). Note that FSA is calculated from the resting foot angle (not shown) minus the foot angle at foot strike (yellow lines on inset images). All values represent means \pm s.e.m.

Since muscle size also depends on relative muscle activity patterns (Ahn et al., 2011), the MG:LG muscle bias was measured in a subset of runners ($N=24$) and directly compared with the MG:LG muscle bias from a group of sedentary subjects ($N=23$). The 24 runners (15 female, 9 male; age: 27.0 ± 1.9 years; BMI, 22.3 ± 0.6 kg m $^{-2}$) consisted of 7 FFS (4 female, 3 male), 11 shifter (7 female, 4 male) and 6 RFS (4 female, 2 male) runners. These runners averaged 24.5 ± 3.2 miles per week. By contrast, the 24 sedentary subjects did not perform any exercise regularly.

Subjects were recruited from the Claremont Colleges or surrounding community. Informed consent was obtained from all subjects. All experiments were conducted in accordance with the Institutional Review Board of Harvey Mudd College and Claremont Graduate University.

Muscle bias

Muscle bias, or relative amplitudes of the MG and LG muscle activation patterns, during walking was measured for 24 runners and 23 sedentary subjects. These muscle bias measurements allowed for a direct comparison in muscle thickness between the runners and sedentary subjects because MG muscle thickness correlates with MG bias in sedentary subjects (Ahn et al., 2011). We recorded the activity patterns of the MG and LG muscles using surface electromyography (sEMG) with a wireless data logger and a laptop computer at 4 kHz for 30 s intervals at each speed (Myomonitor IV, EMGworks, Delsys Inc., Natick, MA, USA; Ahn et al., 2014). Bipolar electrodes (Delsys, Inc.) were adhered lengthwise along the MG and LG muscles one-third of the way down the lower leg and at the midpoint of the muscle based on measurements made by a B-mode, real-time ultrasound machine (210DX; 7.5 MHz linear transducer, Medasonics, Mountain View, CA, USA; Ahn et al., 2011; Ahn et al., 2014). The wires were secured to the leg with self-adherent athletic wrap to minimize movement artifact in the sEMG signals. Amplitudes of the sEMG were normalized to each subject's maximum voluntary contraction using a calf raise machine. Amplitude values of the sEMG were obtained by finding the maximum average of a 10 ms period during the major burst for each stride at each speed (0.3, 0.6, 0.9, 1.2,

1.5 m s $^{-1}$). A subject was designated as 'unbiased' if their muscle bias (MG amplitude divided by the sum of the MG and LG amplitudes) measurements fell within the range 0.33–0.66 and 'MG-biased' if their muscle bias exceeded 0.67 for at least three of the five walking speeds (Ahn et al., 2011).

Normalized gastrocnemius muscle thickness

Muscle size, or the 'thickness', of the MG and LG was measured at 30% of the length down the lower leg using a B-mode, real-time ultrasound machine (Medasonics, 210DX; 7.5 MHz linear transducer; Ahn et al., 2011). The measurement from the ultrasound image was taken from the thickest part of the gastrocnemius muscle and measured from the inner edges of the aponeuroses closest to the skin (NIH ImageJ). To account for variation in the subject size, muscle thickness measurements of the gastrocnemii were normalized to each subject's lower leg length, which was determined from the popliteal crease to the lateral malleolus.

Foot strike pattern

To determine foot strike pattern, the runners ($N=41$) were videorecorded with a high-speed light camera (208 frames s $^{-1}$; AVT Pike 032C Camera, Allied Vision Technologies, Newburyport, MA, USA) while running on a motorized treadmill at four speeds (2.5, 2.8, 3.2 and 3.5 m s $^{-1}$). These runners ran at each speed while unshod or 'barefoot' in lightweight, five-toed socks (45 g; Injinji, Inc., San Diego, CA) that mechanically mimicked the barefoot condition while protecting the participants' feet from the treadmill belt (Ahn et al., 2014). Additionally, runners ran 'shod' in provided supportive, cushioned running shoes (Asics GEL Cumulus; Ahn et al., 2014). For each speed, the video frame of initial foot contact was determined and the angle was measured between a horizontal line and markers on the runners' ankles and the base of their fifth metatarsal (Fig. 1). Foot strike angle (FSA) was measured as the difference between the initial contact angle and a resting angle taken when the participant stood with the same shod condition. At each of the four running speeds, FSA was measured and averaged for five strides because FSA can vary with speed, with more intra-individual variability in runners with less training (Lieberman et al., 2015).

The median FSA of the four speeds was used to determine a final FSA measurement, which categorized the subject as a rearfoot strike (RFS) or a forefoot strike (FFS) runner (Altman and Davis, 2012). A median FSA greater than 8 deg indicated that a subject used a RFS pattern and landed on their heel during running (Fig. 1; Ahn et al., 2014). If the subject consistently used a RFS or FFS when running when barefoot and shod, they were categorized respectively. If the subject changed their foot strike pattern from FFS when barefoot to RFS when shod, then they were determined to be a ‘shifter’.

Plantarflexor moment arm

Plantarflexor moment arm (r) was determined by averaging the horizontal distance from the center of the lateral and medial malleoli to the back of the calcaneal (or Achilles) tendon of digital images of the subject standing at rest while barefoot without socks (Scholz et al., 2008; NIH ImageJ).

Statistics

All statistical comparisons were completed using an unpaired t -test or an ANOVA with *post hoc* Tukey HSD test. Differences were considered significant when $P < 0.05$. All reported values represent means \pm s.e.m.

RESULTS AND DISCUSSION

As hypothesized, FFS runners had longer r than RFS runners (Fig. 2; FFS: 3.89 ± 0.11 cm, RFS: 3.32 ± 0.13 cm; $N=41$; ANOVA with *post hoc* Tukey HSD; $P < 0.05$). The r of the shifters spanned that of FFS and RFS runners, and did not differ from either group (shifters: 3.56 ± 0.12 cm; $P > 0.05$). Runners with longer r tended to FFS and runners with shorter r tended to RFS when barefoot and shod (Fig. 1).

All three groups of runners (FFS, shifters and RFS) had similarly sized gastrocnemii muscles, which rejects our hypothesis that FFS runners would have the largest MG and LG muscles (Fig. 2A). All runners had similar MG muscle thicknesses (FFS: 0.056 ± 0.003 , shifters: 0.055 ± 0.003 , RFS: 0.056 ± 0.003 ; $P=0.71$) and similar LG muscle thicknesses (FFS: 0.044 ± 0.004 , shifters: 0.038 ± 0.002 , RFS: 0.043 ± 0.004 ; $P=0.41$). The MG is typically thicker than the LG muscle in humans (Fig. 2A; Abe et al., 2000). The similar MG and LG muscle thickness among FFS, shifters and RFS runners suggests a possible peak muscle thickness reached by recreational and trained

distance runners. MG and LG muscle size does not vary among runners with different foot strike patterns (Fig. 2A).

Since MG muscle size depends on muscle activation patterns during walking in sedentary individuals (Ahn et al., 2011), we compared the muscle bias of 24 runners with that of 23 sedentary subjects. As with the larger group of 41 runners, this subset of 24 runners consisted of FFS runners that had 20% longer r than RFS runners (ANOVA with *post hoc* Tukey HSD; $P < 0.05$). During walking, half of the runners (11 of 24, or 46%) activated their MG and LG muscles equally (muscle bias: 0.55 ± 0.03) and half the runners (13 of 24, or 54%) activated their MG muscles much more strongly than their LG muscles during walking (muscle bias: 0.72 ± 0.02). Like the runners, half the sedentary subjects (12 of 23, or 52%) used an unbiased recruitment pattern (muscle bias: 0.58 ± 0.02) and half of the sedentary subjects (11 of 23, or 48%) used an MG-biased recruitment pattern (muscle bias: 0.82 ± 0.02) during walking (Fig. 2B). No subject in either group was LG-biased (muscle bias < 0.33 ; Ahn et al., 2011).

For only sedentary subjects, unbiased subjects had smaller MG muscles than those in MG-biased subjects (Fig. 2B; $N=23$; Ahn et al., 2011). The MG muscle thickness of unbiased sedentary subjects was 16–23% smaller than muscles in MG-biased sedentary subjects, unbiased runners and MG-biased runners (Fig. 2B; MG normalized thickness: 0.045 ± 0.004 cm; ANOVA with *post hoc* Tukey HSD; $P < 0.05$). MG thickness was similar for MG-biased sedentary subjects, unbiased runners and MG-biased runners (Fig. 2B; $P > 0.05$). The LG muscle, however, was similarly sized for all four groups (Fig. 2B; $P > 0.05$). The current study did not examine muscle growth over time or with training and can only compare sedentary subjects with runners. The similar MG muscle thickness in MG-biased sedentary subjects and the runners implies a possible peak or plateau in muscle thickness reached in MG-biased sedentary individuals and not exceeded in runners (Fig. 2B).

Plantarflexor muscles of FFS runners may hypertrophy due to earlier and longer activation, and possible lengthening contractions (Higbie et al., 1996; Kawakami et al., 2002; Ahn et al., 2014). The heel strike in RFS runners, who plantarflex the ankle at the beginning of stance, corresponds with shortening of MG muscle fascicles (Lichtwark et al., 2007; Cronin et al., 2011). The FFS, however, likely acts as a counter-movement of the ankle where the runner dorsiflexes upon landing with the fore- or midfoot before plantarflexing. Even

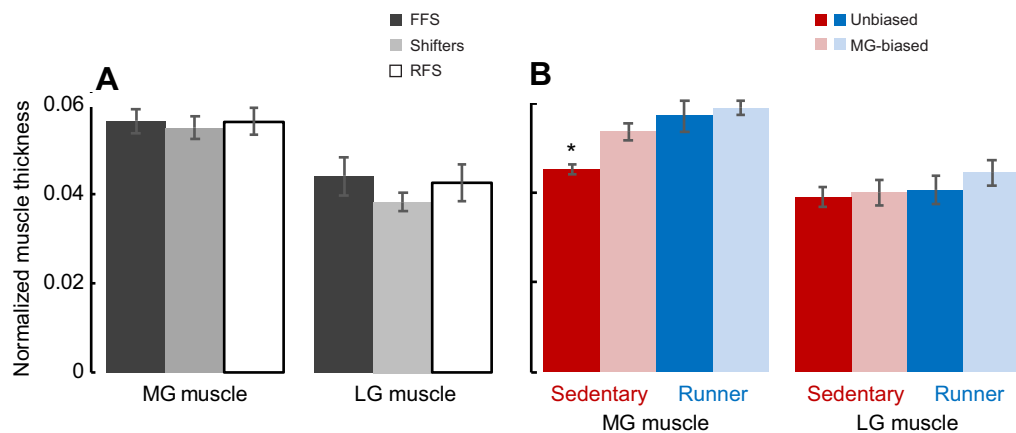


Fig. 2. Normalized calf muscle thickness for all subjects. (A) Gastrocnemius muscle thickness of runners ($N=41$). MG and LG muscle sizes were similar amongst FFS runners ($N=14$), shifters ($N=19$) and RFS runners ($N=8$). (B) Gastrocnemius muscle thickness of sedentary individuals ($N=23$) versus runners ($N=24$). MG muscles of unbiased sedentary subjects ($N=12$) were 16–23% smaller than in all other subjects (ANOVA with *post hoc* Tukey HSD; $*P < 0.05$). MG muscles of biased sedentary subjects ($N=11$), unbiased runners ($N=11$) and biased runners ($N=13$) were similar in size. LG muscles of all subjects were similar in size.

though muscle fiber behavior can be uncoupled from muscle–tendon unit and ankle kinematics due to series elasticity (Griffiths, 1991; Fukunaga et al., 2001; Shin et al., 2009), counter-movement exercises are characterized as lengthening contractions (Kawakami et al., 2002). Early activation of plantarflexor muscles during a counter-movement like a FFS (Ahn et al., 2011) likely results in active lengthening contractions of the plantarflexor muscles. These lengthening contractions may contribute towards hypertrophy of the plantarflexor muscles in unbiased runners who FFS (Higbie et al., 1996). However, the mechanical advantage of a longer r may counter the possible hypertrophic effects of earlier activation and lengthening contractions of FFS running because individuals with longer r also require less force to generate a plantarflexion torque.

FFS runners have longer r than RFS runners, but the two groups have similarly sized plantarflexor muscles. The consistent MG muscle size between FFS versus RFS, and between unbiased versus MG-biased runners indicates that the contraction dynamics of the ankle plantarflexor muscles may balance with the effects of ankle morphology in determining MG and LG muscle size.

Acknowledgements

We would like to thank the Keck Science Department (KSD) and the Harvey Mudd College (HMC) Biology Department for support. We also thank John Milton (KSD) for advising L.S.W. through this process and use of his Delsys equipment for the experiments. We thank Sheila Panez (KSD), Sarah Stevens, Musa Kiyani, Christian Stevens, Parker Martin, Teri Cinco, Chris Jerry (KSD), Charlie Brayton and Tania Bhatia (KSD) for assistance with data collection.

Competing interests

The authors declare no competing or financial interests.

Author contributions

Conceptualization: A.N.A.; Methodology: A.N.A.; Validation: A.N.A.; Formal analysis: L.W., A.N.A.; Investigation: L.W., A.N.A.; Data curation: L.W., A.N.A.; Writing - original draft: L.W.; Writing - review & editing: A.N.A.; Visualization: L.W., A.N.A.; Supervision: A.N.A.; Project administration: A.N.A.; Funding acquisition: A.N.A.

Funding

The project was funded by Barbara Stokes Dewey fellowship to A.N.A., National Science Foundation UBM-0634592 to John Milton (KSD), and Howard Hughes Medical Institute awards 52006301 and 52007544 to Harvey Mudd College.

References

Abe, T., Kumagai, K. and Brechue, W. F. (2000). Fascicle length of leg muscles is greater in sprinters than distance runners. *Med. Sci. Sports Exerc.* **32**, 1125-1129.

- Ahn, A. N., Kang, J. K., Quitt, M. A., Davidson, B. C. and Nguyen, C. T. (2011). Variability of neural activation during walking in humans: short heels and big calves. *Biol. Lett.* **7**, 539-542.
- Ahn, A. N., Brayton, C., Bhatia, T. and Martin, P. (2014). Muscle activity and kinematics of forefoot and rearfoot strike runners. *J. Sport Health Sci.* **3**, 1-11.
- Altman, A. R. and Davis, I. S. (2012). A kinematic method for footstrike pattern detection in barefoot and shod runners. *Gait Posture* **35**, 298-300.
- Baxter, J. R. and Piazza, S. J. (2014). Plantar flexor moment arm and muscle volume predict torque-generating capacity in young men. *J. Appl. Physiol.* **116**, 538-544.
- Cavanagh, P. R. and LaFortune, M. A. (1980). Ground reaction forces in distance running. *J. Biomech.* **13**, 397-406.
- Cronin, N. J., Carty, C. P., Barrett, R. S. and Lichtwark, G. (2011). Automatic tracking of medial gastrocnemius fascicle length during human locomotion. *J. Appl. Physiol.* **111**, 1491-1496.
- Farris, D. J. and Sawicki, G. S. (2012). Human medial gastrocnemius force–velocity behavior shifts with locomotion speed and gait. *Proc. Nat. Acad. Sci. USA* **109**, 977-982.
- Fukunaga, T., Kubo, K., Kawakami, Y., Fukashiro, S., Kanehisa, H. and Maganaris, C. N. (2001). In vivo behaviour of human muscle tendon during walking. *Proc. Roy. Soc. Lond. B Biol. Sci.* **268**, 229-233.
- Griffiths, R. I. (1991). Shortening of muscle fibres during stretch of the active cat medial gastrocnemius muscle: the role of tendon compliance. *J. Physiol.* **436**, 219.
- Higbie, E. J., Cureton, K. J., Warren III, G. L. and Prior, B. M. (1996). Effects of concentric and eccentric training on muscle strength, cross-sectional area, and neural activation. *J. Appl. Physiol.* **81**, 2173-2181.
- Hill, A. V. (1938). The heat of shortening and the dynamic constants of muscles. *Proc. R. Soc. Lond. B Biol. Sci.* **126**, 136-195.
- Kawakami, Y., Muraoka, T., Ito, S., Kanehisa, H. and Fukunaga, T. (2002). In vivo muscle fibre behaviour during counter-movement exercise in humans reveals a significant role for tendon elasticity. *J. Physiol.* **540**, 635-646.
- Komi, P. V. (1986). Training of muscle strength and power: interaction of neuromotoric, hypertrophic, and mechanical factors. *Int. J. Sports Med.* **7**, S10-S15.
- Lichtwark, G. A., Bougoulas, K. and Wilson, A. M. (2007). Muscle fascicle and series elastic element length changes along the length of the human gastrocnemius during walking and running. *J. Biomech.* **40**, 157-164.
- Lieberman, D. E., Venkadesan, M., Werbel, W. A., Daoud, A. I., D'Andrea, S., Davis, I. S. and Pitsiladis, Y. (2010). Foot strike patterns and collision forces in habitually barefoot versus shod runners. *Nature* **463**, 531-535.
- Lieberman, D. E. (2012). What we can learn about running from barefoot running: an evolutionary medical perspective. *Exerc. Sport Sci. Rev.* **40**, 63-72.
- Lieberman, D. E., Castillo, E. R., Otarola-Castillo, E., Sang, M. K., Sigel, T. K., Ojiambo, R. and Pitsiladis, Y. (2015). Variation in foot strike patterns among habitually barefoot and shod runners in Kenya. *PLoS One* **10**, e0131354.
- Raichlen, D. A., Armstrong, H. and Lieberman, D. E. (2011). Calcaneus length determines running economy: implications for endurance running performance in modern humans and Neanderthals. *J. Hum. Evol.* **60**, 299-308.
- Scholz, M. N., Bobbert, M. F., Van Soest, A. J., Clark, J. R. and van Heerden, J. (2008). Running biomechanics: shorter heels, better economy. *J. Exp. Biol.* **211**, 3266-3271.
- Shin, D. D., Hodgson, J. A., Edgerton, V. R. and Sinha, S. (2009). In vivo intramuscular fascicle-aponeuroses dynamics of the human medial gastrocnemius during plantarflexion and dorsiflexion of the foot. *J. Appl. Physiol.* **107**, 1276-1284.