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RESEARCH ARTICLE

Maximum-speed curve-running biomechanics of sprinters with and without unilateral leg amputations

Paolo Taboga[1,2,*], Rodger Kram[2] and Alena M. Grabowski[2,3]

ABSTRACT

On curves, non-amputees' maximum running speed is slower on smaller radii and thought to be limited by the inside leg's mechanics. Similar speed decreases would be expected for non-amputees in both counterclockwise and clockwise directions because they have symmetric legs. However, sprinters with unilateral leg amputation have asymmetric legs, which may differentially affect curve-running performance and Paralympic competitions. To investigate this and understand the biomechanical basis of curve running, we compared maximum curve-running (radius 17.2 m) performance and stride kinematics of six non-amputee sprinters and 11 sprinters with a transtibial amputation. Subjects performed randomized, counterbalanced trials: two straight, two counterclockwise curves and two clockwise curves. Non-amputees and sprinters with an amputation all ran slower on curves compared with straight running, but with different kinematics. Non-amputees ran 1.9% slower clockwise compared with counterclockwise (P<0.05). Sprinters with an amputation ran 3.9% slower with their affected leg on the inside compared with the outside of the curve (P<0.05). Non-amputees reduced stride length and frequency in both curve directions compared with straight running. Sprinters with an amputation also reduced stride length in both curve-running directions, but reduced stride frequency only on curves with the affected leg on the inside. During curve running, non-amputees and athletes with an amputation had longer contact times with their inside compared with their outside leg, suggesting that the inside leg limits performance. For sprinters with an amputation, the prolonged contact times of the affected versus unaffected leg seem to limit maximum running speed during both straight running and running on curves with the affected leg on the inside.

KEY WORDS: Amputee, Paralympics, Prosthesis, Track and field, Athletics

INTRODUCTION

Locomotor performance along curved paths is a matter of life and death among terrestrial predators and prey. However, because it is difficult to motivate and control the behavior of non-human animals, human running experiments have provided a practical test-bed for exploring the biomechanics of high-speed locomotion on curves. In humans, compared with straight running, maximum running speed is slower on unbanked curves and related to curve radius (Chang and Kram, 2007; Churchill et al., 2015; Ferro and Floria, 2013; Greene, 1985; Luo and Stefanyshyn, 2012). For example, human maximum speed on a 6 m radius unbanked curve is ∼26% slower than straight running (Chang and Kram, 2007). Other species show different curve-running behaviors: on large radii, horses slow down in a manner similar to humans (Tan and Wilson, 2011). In contrast, mice (Walter, 2003) and greyhounds (Usherwood and Wilson, 2005) maintain relatively high speeds on curves compared with straight sprinting. A person running on an unbanked curve must apply a centripetal force to change their direction, while simultaneously applying a vertical force to counteract gravity. At approximately 20% of the contact phase, the vector sum of centripetal and vertical forces, i.e. the resultant force, reaches its maximum (Churchill et al., 2015). Greene (1985) proposed that curve running is slower than straight running because there are physiological limits on the maximum resultant force that an individual can exert on the ground.

Running at a given speed along a smaller curve radius requires greater centripetal force compared with running along a larger curve radius. If Greene (1985) is correct (i.e. the magnitude of the resultant force remains unchanged), the maximum vertical force applied on the ground must be smaller for smaller compared with larger curve radii. Because average vertical force must equal body weight during a stride, a smaller vertical force would necessitate a longer ground contact time or briefer aerial time. Greene's model assumes that the forward distance traveled during foot contact (L_c) remains approximately the same during sprinting; thus, a prolonged contact time (t_c) implies a slower speed during curve running (velocity=L_c/t_c). However, in contrast to Greene's model, Chang and Kram (2007) found empirically that subjects sprinting on unbanked curves generated significantly smaller resultant forces compared with straight sprinting. Thus, maximum speed on curves is not simply limited by a physiological upper limit to resultant force. Further, they found that the leg on the inside of the curve generates smaller resultant forces compared with the outside leg and thus concluded that the inside leg's mechanics limit curve-running maximum speed. Similar to Chang and Kram (2007), but on a larger unbanked curve radius (37.72 m), Churchill et al. (2015) also found smaller ground reaction forces for the inside compared with the outside leg in experienced sprinters. They suggested that alterations to the inside leg's joint positions in the frontal plane during curve running may have an effect on the muscles' ability to generate forces, and therefore limit curve-running performance on unbanked tracks.

The effects of curves on running speed have important consequences for competitive athletics events, in which athletes must run in lanes with different curve radii. Track and field athletes participating in 200 and 400 m events must negotiate one or two curves, respectively, on an outdoor track. On a standard 400 m outdoor track, the curve radius is 36.50 m for lane 1 and 45.04 m for lane 8 [International Association of Athletics Federations (IAAF) Track and Field Facilities Manual 2008, http://www.iaaf.org/about-iaaf/documents/technical]. In the 200 m

[1]University of Udine, Department of Medical and Biological Sciences, P.le M. Kolbe 4, Udine 33100, Italy. [2]Integrative Physiology Department, University of Colorado Boulder, Boulder, CO 80309, USA. [3]Eastern Colorado Healthcare System, Department of Veterans Affairs, Denver, CO 80220, USA.

*Author for correspondence (paolo.taboga@uniud.it)

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List of symbols and abbreviations

AL	affected leg
CCW	counterclockwise
CW	clockwise
IAAF	International Association of Athletics Federations
L_c	forward distance traveled during foot contact
RSP	running-specific prosthesis
SF	stride frequency
SL	stride length
t_a	aerial time
t_c	contact time
t_{sw}	leg swing time
UL	unaffected leg
v	velocity

outdoor event, Greene (1985) calculated a 0.123 s advantage for an elite-level sprinter running in lane 8 compared with lane 1. The effects of curve radius are more profound on indoor tracks, where the recommended minimum radius is 17.2 m (IAAF Track and Field Facilities Manual 2008). The IAAF abandoned indoor 200 m races in 2005 because the athletes assigned to outer lanes showed a clear advantage over those assigned to inner lanes (Usherwood and Wilson, 2006).

For non-amputee athletes, similar maximal curve-running speeds would be expected for clockwise (CW) and counterclockwise (CCW) directions because their legs are essentially symmetric. In contrast, the legs of sprinters with a unilateral leg amputation are asymmetric and performance may differ depending on whether the affected leg is on the inside or outside of the curve. Because athletics competitions, including the Paralympic Games, are always run in the CCW direction, it is important to understand the curve-running performance differences between sprinters with a right versus left leg amputation.

Competitive sprinters with leg amputations use running-specific prostheses (RSP), which are typically J-shaped carbon-fiber passive springs intended to replicate the sagittal plane actions of a biological ankle. During the first half of the stance phase, a runner loads the RSP, storing elastic energy. During the second half of the stance phase, the RSP returns a large portion of the elastic energy. However, the compliance and passive nature of RSP impair the application of force on the ground (Grabowski et al., 2010; McGowan et al., 2012), which is the major determinant of maximum sprinting speed (McMahon and Greene, 1979; Weyand et al., 2000). At maximal sprinting speeds during straight running, athletes with a transtibial amputation generate ~16% smaller peak vertical forces with their affected leg compared with their unaffected leg (Grabowski et al., 2010). Sprinters with a transtibial amputation also exhibit a 17% decrease in their affected leg stiffness across running speeds up to top sprinting speeds, whereas non-amputee sprinters significantly increase their leg stiffness with speed (McGowan et al., 2012). However, it has been argued that athletes with transtibial amputations can run with unnaturally short leg swing times because of the lower moment of inertia of RSP compared with biological legs (Weyand and Bundle, 2010). Shorter leg swing times could result in faster stride frequencies. Because velocity equals the product of stride frequency and stride length, RSP could hypothetically enhance running speed. But, stride frequency data for sprinters with a leg amputation do not indicate clear stride frequency enhancements (Grabowski et al., 2010; Kram et al., 2010). In addition, RSP are torsionally stiff and resist inversion/eversion, which may impede the optimal inversion and eversion necessary for unbanked curve running (Greene, 1987; Luo and Stefanyshyn, 2012).

To our knowledge, no previous study has measured the biomechanics of curve running in athletes with leg amputations. Here, we compared the straight and curve-running performance of non-amputee sprinters and sprinters with unilateral transtibial amputation. Further, we investigated the basic stride kinematic changes responsible for any differences in performance observed using the framework of Eqns 1–4. The two following equations define the relationships between average velocity (v) and stride kinematics in a symmetrical bipedal runner:

$$v = \frac{L_c}{t_c}, \tag{1}$$

$$v = \mathrm{SF} \times \mathrm{SL}, \tag{2}$$

where SF is stride frequency and SL is stride length. Further, in a symmetric runner, stride frequency can be expressed in two ways:

$$\mathrm{SF} = \frac{1}{2 \times (t_c + t_a)}, \tag{3}$$

$$\mathrm{SF} = \frac{1}{t_c + t_{sw}}, \tag{4}$$

where t_a is aerial time and t_{sw} is leg swing time.

We expected that both groups would be slower during maximal-speed curve running compared with straight running. However, given that the inside leg is thought to limit curve-running speed (Chang and Kram, 2007), we hypothesized that sprinters with a leg amputation would be slower on curves with their affected leg on the inside of the curve compared with curves with their affected leg on the outside of the curve. We further hypothesized that slower speeds with the affected leg on the inside would be associated with prolonged contact times, because of the force impairment of RSP (Grabowski et al., 2010), similar stride frequencies and shorter stride lengths. Overall, this experiment provided a novel test of the idea that the inside leg limits curve-running performance and a more complete quantification of the underlying stride kinematics.

MATERIALS AND METHODS

Subjects

Seventeen subjects participated: six (5 male/1 female) non-amputee sprinters, six (5 male/1 female) sprinters with a right leg transtibial amputation, and five (2 male/3 female) sprinters with a left leg transtibial amputation (Table 1). All subjects provided informed consent as per the University of Colorado Institutional Review Board.

Experimental design

Each subject performed six 40 m sprints on a standard, unbanked synthetic track surface, wearing their own spiked shoes: two straight sprints, two sprints on a CW curve (radius 17.2 m) and two sprints on a CCW curve (radius 17.2 m). Prior to testing, we performed a pilot study and found no decrement in performance after six 40 m sprints with 8 min of rest in between, but did find that subjects exhibited a decrement in performance after eight sprints that was likely due to fatigue. Thus, we had subjects perform no more than six sprints. We marked the start, 20 m and 40 m marks on the ground with tape. Subjects ran as fast as possible from a standing start. Between each trial, 8 min of rest were enforced. To control for any potential effects of fatigue, for each subject, we selected a random sequence of straight, CW and CCW directions for the first set of three sprints and reversed the sequence for the second set of three sprints. For example, one possible sequence was: CW–straight–CCW–CCW–straight–CW.

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Table 1. Subject characteristics

	Subject	Sex	Age (years)	Height (m)	Mass (kg)	100 m PR (s)	RSP model
Non-amputees	1	M	18	1.73	66.7	11.58	–
	2	M	44	1.75	75.1	11.80	–
	3	M	33	1.75	65.8	12.22	–
	4	M	22	1.80	95.0	12.30	–
	5	M	19	1.82	96.0	12.96	–
	6	F	24	1.65	74.1	14.75	–
Mean±s.d.			26.7±10.0	1.75±0.06	78.8±13.5	12.60±1.15	
Right amputees	1	M	29	1.83	73.9	11.90	Ottobock Sprinter
	2	M	33	1.91	112.3	12.14	Ottobock Sprinter
	3	M	24	1.75	74.5	12.40	Össur Cheetah
	4	M	28	1.88	79.6	12.60	Össur Flexfoot Sprint
	5	M	28	1.70	60.7	26.33 (200 m)	Össur Cheetah
	6	F	21	1.70	59.0	15.63	Ottobock Sprinter
Mean±s.d.			27.2±4.2	1.80±0.09	76.7±19.3	12.98±1.37	
Left amputees	1	F	27	1.70	64.2	13.61	Ottobock Sprinter
	2	M	18	1.78	92.2	14.50	Össur Cheetah
	3	F	20	1.59	56.5	14.65	Ottobock Sprinter
	4	M	27	1.88	75	14.83	Freedom Innovations Catapult
	5	F	27	1.79	71.8	16.29	Össur Flex Run
Mean±s.d.			23.8±4.4	1.75±0.11	71.9±13.4	14.78±0.97	

Demographic and anthropometric variables and 100 m personal records (PR) of non-amputee and amputee subjects. Each amputee subject's running-specific prosthesis (RSP) model is reported. Means±s.d. are reported for all groups. Mean 100 m time for right amputees was calculated assuming one-half of the 200 m personal record of subject 5.

We used a high-speed video camera (Casio EX-FH20, Casio Computer Co., Ltd, Tokyo, Japan) with a frame-rate of 210 frames s^{-1} to record each subject during each trial (Fig. 1). We analyzed each trial using Kinovea 0.8.15 software (Joan Charmant & Contrib., http://www.kinovea.org). We calculated mean running velocity between the 20 and 40 m marks by identifying the beginning and end of the time interval when the subject's chest crossed the marks on the ground. For each leg, we measured ground contact time, leg swing time (subsequent to the leg's contact time), aerial time (subsequent to the leg's contact time) and stride time (the time from mid-stance to ipsilateral mid-stance; see Fig. 2). In this paper, we designated each aerial time as the time following the contact time of the same leg, bearing in mind that the attribution of an aerial time to one specific leg is arbitrary. It should be noted, however, that due to the interaction between legs, the preceding aerial phase influences the subsequent stance phase. Finally, we multiplied stride time by running velocity to obtain stride length.

Statistical analysis

We checked the normality of the samples with the Shapiro–Wilk test and then used paired samples *t*-tests to assess differences in velocity and stride kinematics between straight, CCW and CW running in non-amputees and sprinters with amputations. We subsequently combined sprinters with a left or right leg

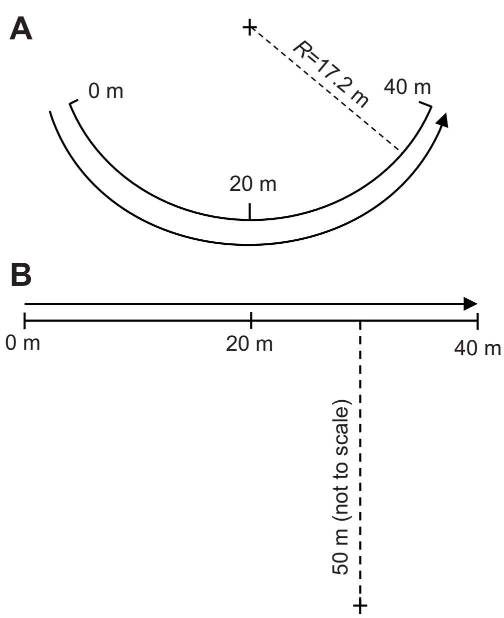

Fig. 1. Top view of the experimental setup. Counterclockwise (CCW) curve (A) and straight track (B). For the clockwise (CW) curve, subjects started from the 40 m mark in A and ran to the 0 m mark. All measurements were performed for the last 20 m of each run. The plus sign indicates camera placement. *R*, radius.

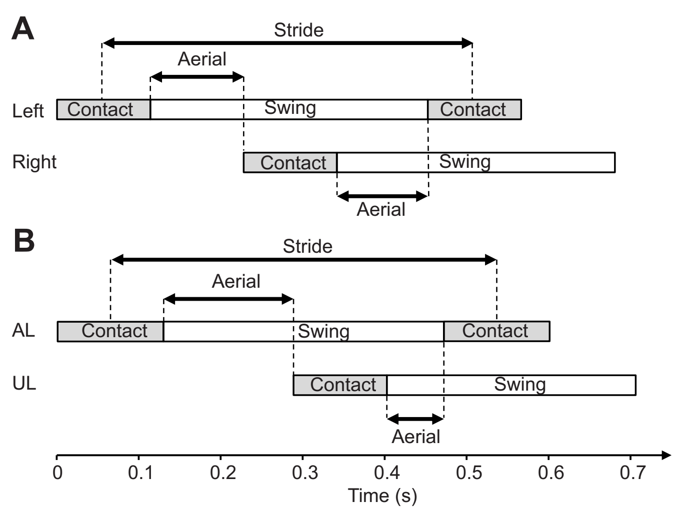

Fig . 2. Schematic view of the measured stride kinematics versus time. (A) Non-amputees. (B) Sprinters with an amputation. Stride time is the time from mid-stance to ipsilateral mid-stance. Aerial time is the time from the end of foot–ground contact to the beginning of contralateral foot–ground contact. Non-amputees (A) have a symmetric running gait, while sprinters with a unilateral amputation (B) have longer contact times and aerial times with their affected leg (AL) compared with their unaffected leg (UL).

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Table 2. Average stride lengths (SL) and stride frequencies (SF)

	Straight		CCW		CW	
	SL (m)	SF (Hz)	SL (m)	SF (Hz)	SL (m)	SF (Hz)
Non-amputees	3.73±0.23	2.16±0.10	3.52±0.19*	2.10±0.12*	3.48±0.17*	2.08±0.10*
Right leg amputation	3.86±0.39	2.08±0.09	3.67±0.23*	**2.07±0.08**	3.62±0.19*	**1.96±0.08***
Left leg amputation	3.47±0.20	2.06±0.16	3.41±0.16	1.94±0.14*	3.33±0.20*	2.00±0.15
	Straight		AL outside		AL inside	
	SL (m)	SF (Hz)	SL (m)	SF (Hz)	SL (m)	SF (Hz)
All amputees	3.69±0.37	2.07±0.12	3.52±0.27*	**2.04±0.12**	3.53±0.20*	**1.95±0.10***

Asterisks represent differences between the straight- versus curve-running trials. Bold values indicate a significant difference between CCW and CW curves. During curve running, non-amputees took shorter strides (*P*=0.005, *P*=0.002) and reduced stride frequency (*P*=0.008, *P*=0.017) in both CCW and CW directions, compared with straight-running trials. Sprinters with a right leg amputation took shorter strides during CCW (*P*=0.034) and CW curves (*P*=0.040) compared with straight-running trials, and also reduced stride frequency during CW curves compared with straight-running trials (*P*=0.011) and compared with CCW curves (*P*=0.014). Sprinters with a left leg amputation took shorter strides during CW curves (*P*=0.018) and reduced stride frequency during CCW curves (*P*=0.001) compared with straight-running trials. All sprinters with an amputation took shorter strides during curve-running trials compared with straight-running trials [*P*=0.003 and *P*=0.017 on curves with the affected leg (AL) on the outside and on curves with the AL on the inside, respectively], and reduced stride frequency only on curves with the AL on the inside compared with curves with the AL on the outside (*P*=0.01) and compared with straight-running trials (*P*<0.001).

amputation into a single group and distinguished curves when runners had their affected leg on the inside versus the outside of the curve. We used one-tailed paired samples *t*-tests to assess velocity and kinematic differences between these conditions. *P*<0.05 was considered significant. To elucidate how a left versus right leg amputation affected performance, we also present data for athletes with left and right leg amputation in Tables 1 and 2. All data are presented as means±s.d.

RESULTS

Speed

Compared with straight running, non-amputee sprinters ran CCW and CW curves 8.9% and 11.0% slower, respectively (*P*=0.001 for both conditions; Fig. 3), and ran 1.9% slower on CW compared with CCW curves (*P*=0.042).

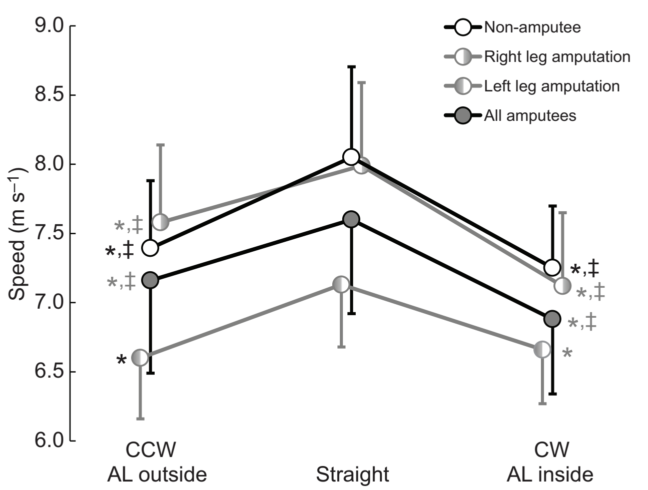

Fig. 3. Mean (±s.d.) maximum speed for straight, CCW and CW curve running. Curve radius was 17.2 m. Non-amputees were slower during CCW and CW curve running compared with straight running (*P*=0.001 for both conditions) and ran slower on CW compared with CCW curves (*P*=0.042). All athletes with amputations ran slower during curve running compared with straight running (*P*<0.001). Moreover, they were slower during curve running when their AL was on the inside compared with on the outside of the curve (*P*=0.032). Asterisks represent significant differences between straight- and curve-running trials. Double daggers indicate significant differences between CCW and CW directions or between the AL on the outside and the AL on the inside of the curve. See Table S1 for values.

Compared with straight running, sprinters with an amputation ran 6.1% slower with their affected leg on the outside of the curve and 10.5% slower with their affected leg on the inside of the curve (*P*<0.001). Running speed was 3.9% slower on curves with their affected leg on the inside compared with on the outside of the curve (*P*=0.032).

Contact time

During straight running, non-amputees had symmetric left and right leg contact times (Fig. 4). During curve running, inside and outside leg contact times were 20% and 12% longer, respectively, compared with straight running contact time (*P*<0.01 for all comparisons). The inside leg contact time was 8% longer than the outside leg contact time regardless of the curve direction (*P*=0.04 and *P*<0.001 for CW and CCW curves, respectively).

During straight running, sprinters with an amputation had 11% longer contact times for their affected leg compared with their unaffected leg (*P*<0.001). Compared with straight running, both the affected and unaffected legs had longer contact times during curve running, regardless of direction, but the effect was more pronounced for the inside leg. In particular, affected leg contact times were 14% longer on curves compared with straight running when the affected leg was on the inside of the curve (*P*<0.001), and unaffected leg contact times were 18% longer for curves compared with straight running when the unaffected leg was on the inside of the curve (*P*<0.001). During curve running with their affected leg on the inside of the curve, subjects had 13% longer contact times for their affected leg compared with their unaffected leg (*P*<0.001). When the affected leg was on the outside of the curve, there were no significant differences in contact times between the affected and unaffected legs.

Stride frequency

Compared with straight running, non-amputees reduced their stride frequency by 2.4% (*P*=0.008) and 3.4% (*P*=0.017) on CCW and CW curves, respectively (Table 2).

Compared with straight running, sprinters with an amputation reduced their stride frequency by 5.6% (*P*<0.001) on curves with their affected leg on the inside, but did not change stride frequency on curves with the affected leg on the outside. Stride frequency was 4.2% slower on curves with the affected leg on the inside compared with curves with the affected leg on the outside (*P*=0.010).

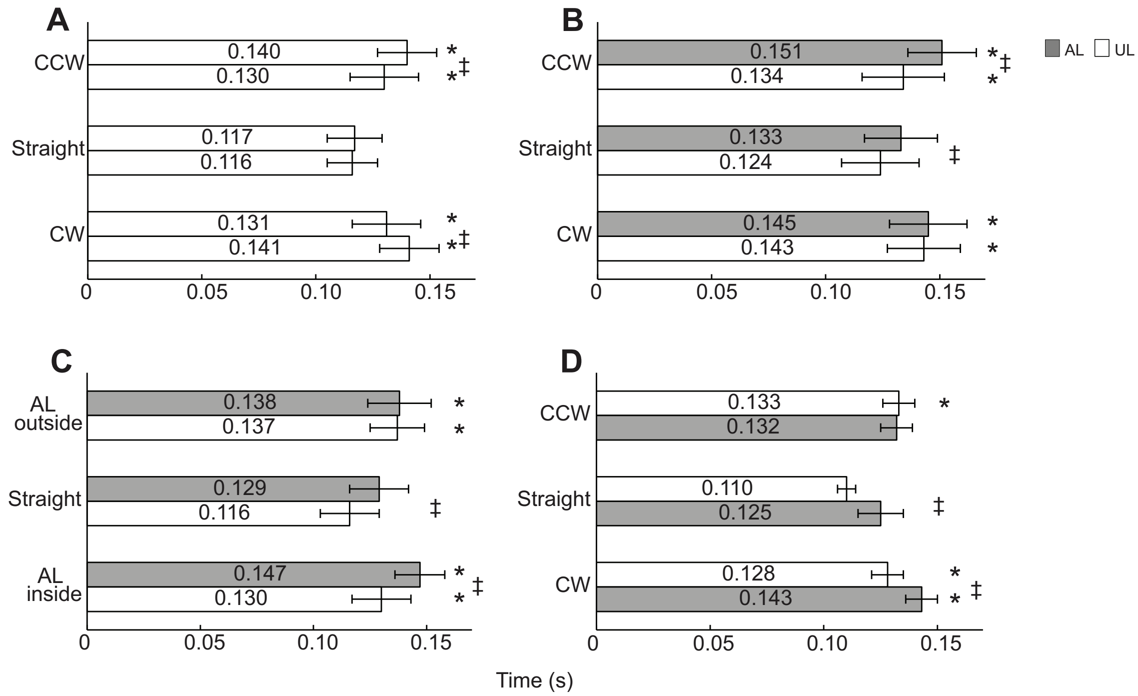

Fig. 4. Mean (±s.d.) contact times for straight, CCW and CW curve running. Curve radius was 17.2 m. (A) Non-amputees had longer contact times in curve-running trials compared with straight-running trials (P<0.01 for all comparisons). In addition, they had longer left leg contact times in CCW curves (P=0.04) and right leg contact times in CW curves (P<0.001). (B) Sprinters with a left leg amputation had longer left leg (AL) contact times in the straight (P=0.011) and CCW (P=0.006) directions compared with right leg (UL) contact times. (D) Sprinters with a right leg amputation had longer right leg (AL) contact times in the straight (P=0.004) and CW (P=0.007) directions compared with left leg (UL) contact times. There were no differences in right (AL) and left (UL) leg contact times in the CCW direction. (C) All sprinters with an amputation had longer AL compared with UL contact times during straight running (P<0.001) and during curve running with their AL on the inside (P<0.001). Asterisks represent significant differences between the same leg in straight versus curve running. Double daggers indicate significant differences between the left and right legs, and between the AL and UL in the same condition (straight, CCW, CW, AL on the outside, or AL on the inside of the curve).

Stride length

Compared with straight running, non-amputee sprinters shortened their stride length by 5.6% (P=0.005) and 6.7% (P=0.002) on CCW and CW curves, respectively (Table 2).

Compared with straight running, sprinters with an amputation reduced their stride length by 4.3% (P=0.017) on curves with their affected leg on the inside and by 4.6% (P=0.003) on curves with their affected leg on the outside.

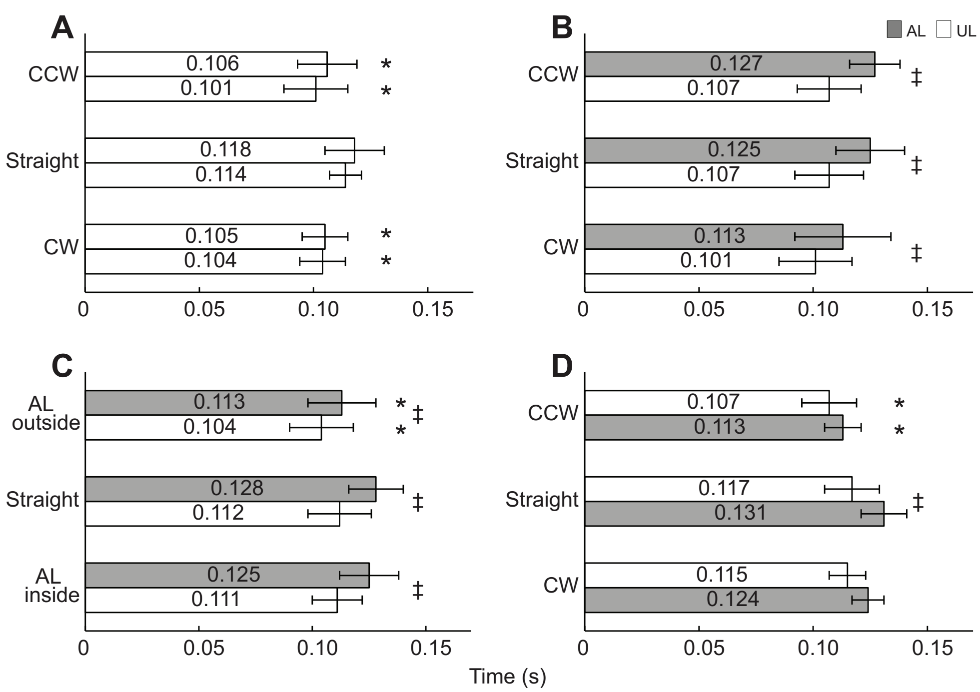

Fig. 5. Mean (±s.d.) aerial times for straight, CCW and CW curve running. Curve radius was 17.2 m. (A) Non-amputees had symmetric aerial times in all conditions. (B) Sprinters with a left leg amputation had longer left leg (AL) compared with right leg (UL) aerial times during straight-running (P=0.011), CCW (P<0.001) and CW (P=0.019) trials. (D) Sprinters with a right leg amputation had longer right leg (AL) compared with left leg (UL) aerial times during straight-running trials (P=0.048). (C) All sprinters with an amputation had longer AL compared with UL aerial times during straight-running trials (P<0.001), curves with the AL on the outside (P=0.020) and curves with the AL on the inside (P=0.012). Asterisks represent significant differences between the same leg in straight- versus curve-running trials. Double daggers indicate significant differences between left and right legs and between the AL and UL in the same condition (straight, CCW, CW, AL on the outside, or AL on the inside of the curve).

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Aerial time

Non-amputees had symmetric aerial times in all conditions (Fig. 5), but during curve running, aerial times were 9–11% shorter compared with straight running.

In contrast, during straight running, sprinters with an amputation had 14% longer aerial times after their affected leg contact compared with after their unaffected leg contact (P<0.001). Compared with straight running, affected leg aerial times were 12% shorter (P=0.003) and unaffected leg aerial times were 7% shorter (P=0.005) on curves with the affected leg on the outside. Compared with straight running, affected and unaffected leg aerial times were not significantly different on curves with the affected leg on the inside. On curves with their affected leg on the inside, subjects had 13% longer affected leg aerial times compared with unaffected leg aerial times (P=0.012). On curves with their affected leg on the outside, sprinters with an amputation had 9% longer affected leg aerial times compared with unaffected leg aerial times (P=0.020).

Leg swing time

During straight running, non-amputees had symmetric left and right leg swing times (Fig. 6). But, during curve running, inside leg swing times were 3% shorter compared to outside leg swing times in both directions (P=0.04 and P=0.004 in CCW and CW running directions, respectively).

During straight running, sprinters with an amputation had 3% shorter affected leg swing times compared with unaffected leg swing times (P<0.001). Compared with straight running, sprinters with an amputation reduced their unaffected leg swing time when it was on the inside and increased unaffected leg swing time when it was on the outside of the curve. Compared with straight running, subjects increased their affected leg swing times on curves when the affected leg was on the inside, but did not change affected leg swing time on curves when it was on the outside of the curve. On curves with the affected leg on the inside, subjects had 4% shorter affected leg swing times compared with unaffected leg swing times (P<0.001). On curves with the affected leg on the outside, there were no significant differences between affected and unaffected leg swing times.

DISCUSSION

As expected, all sprinters were slower during maximal sprint curve running compared with maximal sprint straight running (−10% and −8% on average for non-amputees and sprinters with an amputation, respectively). In support of our first hypothesis, sprinters with an amputation were 3.9% slower on curves with the affected leg on the inside compared with curves with the affected leg on the outside. Because all track and field competitions are run in the CCW direction, the speed difference between CW and CCW directions in non-amputees is likely attributed to training in the CCW (usual) direction. The speed difference between CW and CCW curves was amplified in sprinters with a right leg amputation; they were much slower when running CW (unusual direction) with their affected leg on the inside of the curve. In contrast, sprinters

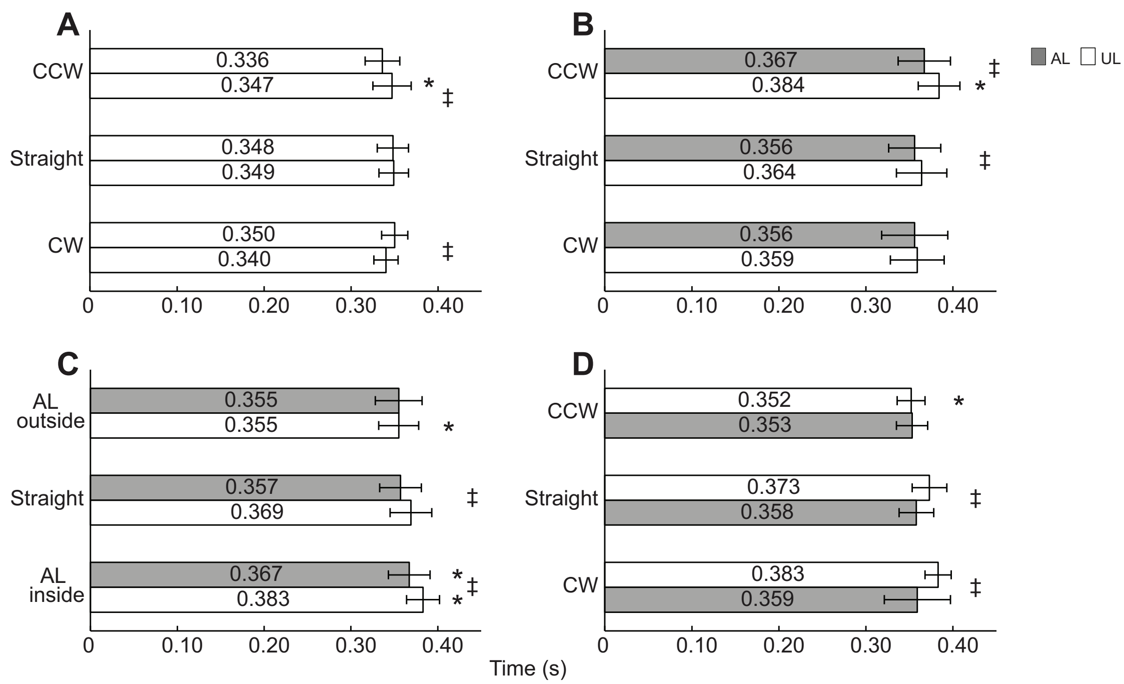

Fig. 6. Mean (±s.d.) leg swing times for straight, CCW and CW curve running. Curve radius was 17.2 m. (A) Non-amputees had shorter left leg swing times during CCW curves (P=0.040) and had longer left leg swing times during CW curves (P=0.004). Left leg swing times were significantly shorter in the CCW direction compared with straight-running trials (P=0.011). (B) Sprinters with a left leg amputation had shorter left leg (AL) swing times compared with right leg (UL) swing times during straight running (P=0.011) and during CCW running (P=0.001). Right leg (UL) swing times were longer in the CCW direction compared with straight-running trials (P=0.010). (D) Sprinters with a right leg amputation had shorter right leg (AL) swing times compared with left leg (UL) swing times during straight running (P<0.001) and during CW running (P<0.001). Left leg (UL) swing times were shorter in the CCW direction compared with straight-running trials (P=0.016). (C) All sprinters with an amputation had shorter AL swing times compared with UL swing times during straight running (P<0.001) and curve running with their AL on the inside (P<0.001). The UL swing times were shorter in curves with the AL on the outside compared with straight running trials (P=0.006), while they were longer in curves with the AL on the inside compared with straight running trials (P=0.035). Asterisks represent significant differences between the same leg in straight- versus curve-running trials. Double daggers indicate significant differences between left and right legs and between affected (AL) and unaffected legs (UL) in the same condition (straight, CCW, CW, AL on the outside or AL on the inside of the curve).

with a left leg amputation did not have significant speed differences between curve-running directions, likely due to speed mitigation when sprinting with their affected leg on the inside of the curve in the CCW (usual) direction compared with sprinting with their affected leg on the outside of the curve in the CW direction (unusual). Thus, the orientation of the affected leg (inside versus outside) seems to limit speed more than curve-running direction.

We partially reject our second hypothesis. Both non-amputees and sprinters with an amputation ran slower on curves, but with different stride kinematics. The speed reduction of non-amputees for both curve-running directions was due to 15% longer average contact times, implying that the distance traveled during foot contact (L_c) increased by 6% on average for both curve-running directions (see Eqn 1). As a consequence of longer contact times (+0.025 s on average) but reduced aerial times (−0.015 s on average) and contrary to our hypothesis, non-amputees reduced stride frequency by 3% for both curve-running directions (see Eqn 3). As L_c was longer during curve running, it is evident that the decreased stride length was due to shorter aerial times (10% on average). But, aerial time did not decrease enough to allow non-amputees to maintain the stride frequency that they used during straight running.

Compared with straight running, sprinters with an amputation increased their contact time by 13% on average for both legs in both curve-running directions. Thus, according to Eqn 1, they must have increased L_c by 7% on average during curve running. On curves with the affected leg on the inside, they reduced stride frequency by 6%, because of increased contact times and similar aerial times compared with straight running. On curves with the affected leg on the outside, they maintained the same stride frequency as for straight running by increasing contact time and reducing aerial time (Eqn 3). McMahon and Greene (1978) demonstrated that faster straight ahead running velocities are associated with exerting greater vertical forces on the ground over shorter contact times. We can interpret our findings based on this principle. During curve running, non-amputees and athletes with an amputation spent more time on the ground with their inside leg compared with their outside leg. These contact time measurements are in accord with those of previous studies (Chang and Kram, 2007; Ryan and Harrison, 2003).

Although we did not perform ground reaction force measurements, previous studies allow some inference. Data from athletes with unilateral leg amputation sprinting straight ahead on a force-measuring treadmill (Grabowski et al., 2010) clearly indicate that the peak vertical ground reaction forces and impulses generated by the affected leg using an RSP are significantly lower than those of the unaffected leg. Data from non-amputees sprinting on curves (Chang and Kram, 2007) suggest that the ground reaction force generated by the inside leg limits curve-running speed. Combining these two findings (longer contact times and presumably lower ground reaction forces), we infer that the curve-sprinting performance of athletes with an amputation was most impaired by their ability to generate force with their affected leg when it was on the inside of the curve. In addition, on curves with the affected leg on the inside, average aerial times, and thus vertical impulses, were the same as during straight running. Recently, Churchill et al. (2015) found that while the inside and outside legs of non-amputee sprinters maintain the same vertical impulses during curve running, the inside leg generates 61% greater centripetal impulse compared with the outside leg. The sprinters with an amputation in the present study may have run slower because they were unable to re-direct ground reaction forces centripetally when the affected leg was on the inside of the curve, likely because of the resistance of RSP to plantar inversion and eversion.

In accord with Grabowski et al. (2010), we found that during straight running, sprinters with an amputation exhibited longer aerial times following affected leg contact compared with unaffected leg contact. These results may seem counterintuitive, given the force impairment of the affected leg (Grabowski et al., 2010). However, as suggested by the same authors, the difference in aerial times may have resulted from longer affected compared with unaffected leg lengths, and/or the necessity for affected leg ground clearance during leg swing. In both symmetric and asymmetric bipedal running, the stride time of one leg must be equal, on average, to the stride time of the other leg. If this rule were violated, a runner would need to take two steps in succession with the same leg after a certain number of steps. In fact, Eqn 4 can be expanded as:

$$\mathrm{SF} = \left(\frac{1}{t_c + t_{sw}}\right)_{\mathrm{AL}} = \left(\frac{1}{t_c + t_{sw}}\right)_{\mathrm{UL}}, \tag{5}$$

where AL and UL refer to affected and unaffected leg, respectively. Athletes with an amputation, who increase the contact time of their affected leg, must therefore decrease the leg swing time of their affected leg by the same amount, as is evident in our measurements (Figs 4 and 6). Grabowski et al. (2010) found no significant differences between the affected and unaffected leg contact times or swing times of athletes with an amputation during straight sprinting, perhaps because of a smaller sample size. The present data show 3% shorter affected compared with unaffected leg swing times during straight running. It is unclear whether this is the result of the lower moment of inertia of RSP compared with biological legs hypothesized in previous studies (Weyand and Bundle, 2010), a compensation for the force impairment of the affected leg (and therefore a direct consequence of the relationship between contact and swing times of Eqn 5), or a combination of these two factors.

Limitations and future studies

We measured the effects of only one curve radius, but different radii could provide more insight into curve running in sprinters with leg amputations. Future measurements of ground reaction forces during curve running in athletes with leg amputations would be useful for testing our inference of a force deficit in the affected leg, determining leg stiffness, and quantifying whether and how forward velocity changes from step to step.

Though it would be of great interest to determine the straight-ahead running speed reduction caused by an individual having unilateral or bilateral leg amputations compared with an individual having two fully biological legs (Weyand et al., 2009), we have not made absolute statistical comparisons between non-amputees and athletes with an amputation because they differ by ∼9% in personal best performances.

Conclusions

As expected, non-amputees and athletes with a leg amputation ran slower on curves compared with straight running. The velocities of non-amputees were only 1.9% different on CW and CCW curves. However, athletes with an amputation were 3.9% slower on curves with the affected leg on the inside, compared with curves with the affected leg on the outside. Slower running speeds on curves were primarily due to prolonged contact times and only partially reduced aerial times. Both groups reduced stride length on curves and non-amputees reduced stride frequency for both curve directions, but

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sprinters with an amputation only reduced stride frequency on curves with the affected leg on the inside. The performance of sprinters with an amputation was most impaired by their ability to generate force with their affected leg when it was on the inside of the curve and they were not able to fully compensate with more rapid affected leg swing times.

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Competing interests

The authors declare no competing or financial interests.

Author contributions

P.T., R.K. and A.M.G. designed the study, P.T. and A.M.G. carried out the measurements and P.T. analyzed the measurements and performed the statistical analyses. All authors contributed to manuscript preparation and approved the final version of the manuscript for publication.

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Supplementary information

Supplementary information available online at http://jeb.biologists.org/lookup/suppl/doi:10.1242/jeb.133488/-/DC1

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