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RESEARCH ARTICLE | *Case Studies in Physiology*

The biomechanics of the fastest sprinter with a unilateral transtibial amputation

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Beck ON, Grabowski AM. The biomechanics of the fastest sprinter with a unilateral transtibial amputation. *J Appl Physiol* 124: 641–645, 2018. First published October 19, 2017; doi:10.1152/japplphysiol.00737.2017.—People have debated whether athletes with transtibial amputations should compete with nonamputees in track events despite insufficient information regarding how the use of running-specific prostheses (RSPs) affect athletic performance. Thus, we sought to quantify the spatiotemporal variables, ground reaction forces, and spring-mass mechanics of the fastest athlete with a unilateral transtibial amputation using an RSP to reveal how he adapts his biomechanics to achieve elite running speeds. Accordingly, we measured ground reaction forces during treadmill running trials spanning 2.87 to 11.55 m/s of the current male International Paralympic Committee T44 100- and 200-m world record holder. To achieve faster running speeds, the present study's athlete increased his affected leg (AL) step lengths ($P < 0.001$) through longer contact lengths ($P < 0.001$) and his unaffected leg (UL) step lengths ($P < 0.001$) through longer contact lengths ($P < 0.001$) and greater stance average vertical ground reaction forces ($P < 0.001$). At faster running speeds, step time decreased for both legs ($P < 0.001$) through shorter ground contact and aerial times ($P < 0.001$). Unlike athletes with unilateral transtibial amputations, this athlete maintained constant AL and UL stiffness across running speeds ($P \geq 0.569$). Across speeds, AL step lengths were 8% longer ($P < 0.001$) despite 16% lower AL stance average vertical ground reaction forces compared with the UL ($P < 0.001$). The present study's athlete exhibited biomechanics that differed from those of athletes with bilateral and without transtibial amputations. Overall, we present the biomechanics of the fastest athlete with a unilateral transtibial amputation, providing insight into the functional abilities of athletes with transtibial amputations using running-specific prostheses.

NEW & NOTEWORTHY The present study's athlete achieved the fastest treadmill running trial ever attained by an individual with a leg amputation (11.55 m/s). From 2.87 to 11.55 m/s, the present study's athlete maintained constant affected and unaffected leg stiffness, which is atypical for athletes with unilateral transtibial amputations. Furthermore, the asymmetric vertical ground reaction forces of athletes with unilateral transtibial amputations during running may be the result of leg length discrepancies.

amputee; force; paralympic; prosthesis; sprint

INTRODUCTION

The fastest humans can achieve running speeds >12 m/s during track competitions (18). Running speed equals the product of stride length and stride frequency, where one stride comprises two steps. Humans increase step length by furthering the horizontal distance traveled by their center of mass (CoM) during ground contact (contact length) and/or by applying a greater average vertical force on the ground relative to body weight (23, 24). Step frequency is improved by decreasing step time, which is the sum of ground contact time and subsequent aerial time (23, 24).

The running speed of athletes with leg amputations is constrained by the same spatiotemporal and vertical ground reaction force (GRF) variables as nonamputees (22). During running, athletes with leg amputations use passive-elastic carbon-fiber running-specific prostheses (RSPs). These devices attach in-series to carbon-fiber sockets that encompass the residual limbs and facilitate the fundamental spring-like behavior of level-ground running (3–5, 19). Unlike biological legs, RSPs cannot generate mechanical power de novo or adjust stiffness neurally during running (1). Also, the overall affected leg stiffness of athletes with unilateral transtibial amputations is inversely related to running speed, whereas their overall unaffected leg stiffness is independent of running speed (19). Despite differences between purely biological and RSP incorporated legs, RSPs have enabled many athletes with leg amputations to compete with nonamputees in track races ranging from regional competitions to the Olympic Games.

The running performances of extraordinary athletes with transtibial amputations have been controversial because of the use of RSPs, rather than purely biological legs (14, 22). However, in spite of the ongoing conversation regarding whether athletes with transtibial amputations should compete with nonamputees in running events (17, 21), the running biomechanics of the fastest athlete with a unilateral transtibial amputation using an RSP are unknown. Thus, to uncover the capabilities of athletes with unilateral transtibial amputations using RSPs, we sought to establish how the fastest athlete with a unilateral transtibial amputation using an RSP modulates spatiotemporal variables, GRFs, and spring-mass mechanics across a wide range of running speeds, including top speed.

METHODS

One male athlete with a unilateral transtibial amputation participated [age: 23 yr, height: 1.90 m, mass: 84.5 kg, unaffected leg (UL)

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length from the greater trochanter to the floor during standing: 1.03 m, affected leg (AL) length from the greater trochanter to the distal end of the unloaded RSP: 1.09 m, cause of amputation: trauma]. We tested this athlete during the preseason of his competition cycle that concluded with two International Paralympic Committee male T44 classification (25) world records: 10.61 s for 100 m and 21.27 s for 200 m (26). Before participation, this athlete gave informed written consent according to the protocol approved by the Colorado Multiple Institutional Review Board and the United States Army Medical Research and Materiel Command Office of Research Protection, Human Research Protection Office.

Protocol. Following a treadmill running warm-up, the athlete performed a set of treadmill running trials (Treadmetrix, Park City, UT) using a stiffness category 7 Össur Cheetah Xtreme RSP (Össur, Reykjavík, Iceland). The running trials were performed in the following order: 2.87, 3.84, 4.60, 5.62, 6.51, 7.50, 8.35, 9.21, 10.14, 10.48, and 11.55 m/s. Each trial began with the athlete standing on the static treadmill belt. Next, he and the treadmill belt accelerated until belt speed plateaued; at that point, we began counting his steps. For each trial, the athlete maintained forward position on the treadmill while taking 18 consecutive steps (14, 19, 22, 24). Ad libitum rest preceded each trial.

Data analysis. Athletes with unilateral transtibial amputations exhibit asymmetric spatiotemporal, GRF, and spring-mass model variables between legs while running (3, 14, 19, 20); accordingly, we quantified the respective variables from each leg separately. We determined running speed (v) as treadmill belt speed. Biomechanically, running speed (v) is the product of step length (L_{step}) and step frequency ($Freq_{step}$).

$$v = (\text{AL } L_{step} \times \text{AL } Freq_{step} + \text{UL } L_{step} \times \text{UL } Freq_{step})/2 \quad (1)$$

Steps lengthen by increasing contact length (L_c) and/or stance average vertical GRF (F_{avg}) relative to body weight (BW) including running gear (23, 24).

$$L_{step} = L_c \times F_{avg}/BW \quad (2)$$

We calculated step frequency as the reciprocal of step time (t_{step}), which equals the sum of the ground contact time (t_c) and subsequent aerial time (t_a) (23, 24).

$$Freq_{step} = \frac{1}{t_{step}} = \frac{1}{t_c + t_a} \quad (3)$$

For our analyses, we calculated L_{step} as t_{step} multiplied by v (treadmill belt speed).

We calculated overall leg stiffness (k_{leg}) as peak vertical GRF (F_{peak}) divided by peak leg spring compression (ΔL) during ground contact in accordance with Farley et al. (12).

$$k_{leg} = \frac{F_{peak}}{\Delta L} \quad (4)$$

We calculated peak leg spring compression (ΔL) using the initial AL and UL lengths (L_0), theta (θ), treadmill speed (v), and ground contact time (t_c).

$$\theta = \sin^{-1}\left(\frac{vt_c}{2L_0}\right) \quad (5)$$

Next, we determined peak leg spring compression (ΔL) using peak vertical displacement of the CoM during ground contact (Δy), calculated by twice integrating the vertical acceleration of the CoM with respect to time (8).

$$\Delta L = \Delta y + L_0(1 - \cos\theta) \quad (6)$$

Data collection. We measured vertical and horizontal GRFs (1,000 Hz) throughout the duration of each trial, filtered them using a 4th order low-pass Butterworth filter (20-Hz cutoff), and then used the filtered data and a 40 N vertical GRF threshold to calculate the variables in *Eqs. 1* through *6* with a custom MATLAB script (Mathworks, Natick, MA).

Statistical analyses. We performed linear regressions for each biomechanical variable from *Eqs. 1* to *6* across running speeds. We used paired two-tailed t-tests to assess the influence of the AL vs. UL on each biomechanical variable across running speeds. We set the level of significance at $P = 0.05$ and performed statistical analyses using R-studio (Boston, MA).

RESULTS

Some trials contained steps where the treadmill and athlete were still accelerating to the target speed. Thus, after we removed all acceleration phase running steps, some trials contained <18 consecutive steps. Nonetheless, all trials comprised ≥6 consecutive steps at a constant running speed (2). In addition, we measured a top speed of 11.55 m/s, which to our knowledge is the fastest treadmill running trial ever recorded for a human with a leg amputation.

From 2.87 to 11.55 m/s, AL and UL t_c decreased 55 and 51%, respectively ($P < 0.001$), and AL and UL t_a decreased 39 and 41%, respectively ($P < 0.001$) (Fig. 1). This led to a 47 and 46% decreased AL and UL t_{step} ($P < 0.001$) and a 107 to 108% increased AL and UL L_{step}, respectively ($P < 0.001$) (Fig. 2). Additionally, from 2.87 to 11.55 m/s, AL L_c increased 82% (AL $L_c = 0.055$ speed $+ 0.478$; $R^2 = 0.93$; $P < 0.001$), UL L_c increased 96% (UL $L_c = 0.052$ speed $+ 0.480$; $R^2 =$

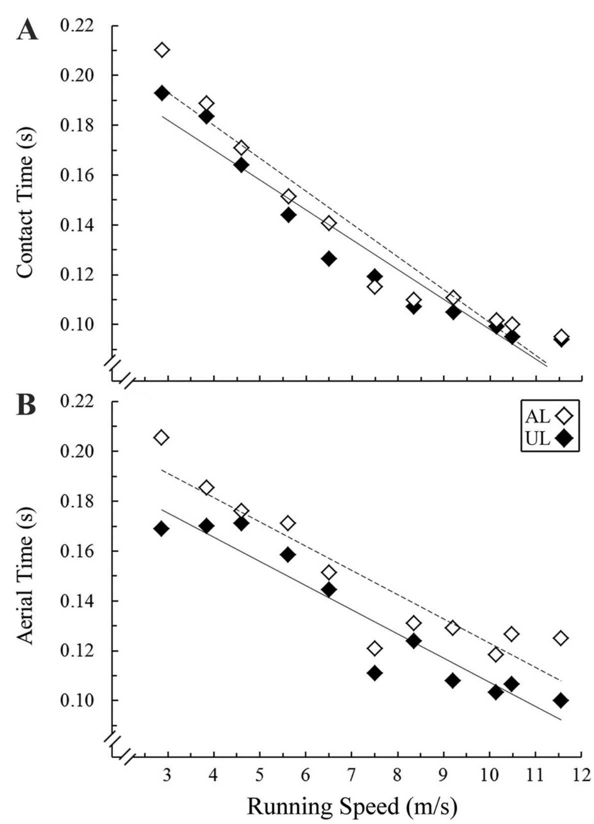

Fig. 1. Ground contact time (t_c, *A*) and aerial time (t_a, *B*) for the AL and UL across running speeds (v). Broken lines, AL regression lines; solid lines, UL regression lines. The following are the respective regression equations: AL $t_c = -0.013v + 0.233$; $R^2 = 0.93$; $P < 0.001$. UL $t_c = -0.012v + 0.218$; $R^2 = 0.93$; $P < 0.001$. AL $t_a = -0.010v + 0.220$; $R^2 = 0.85$; $P < 0.001$. UL $t_a = -0.010v + 0.205$; $R^2 = 0.90$; $P < 0.001$.

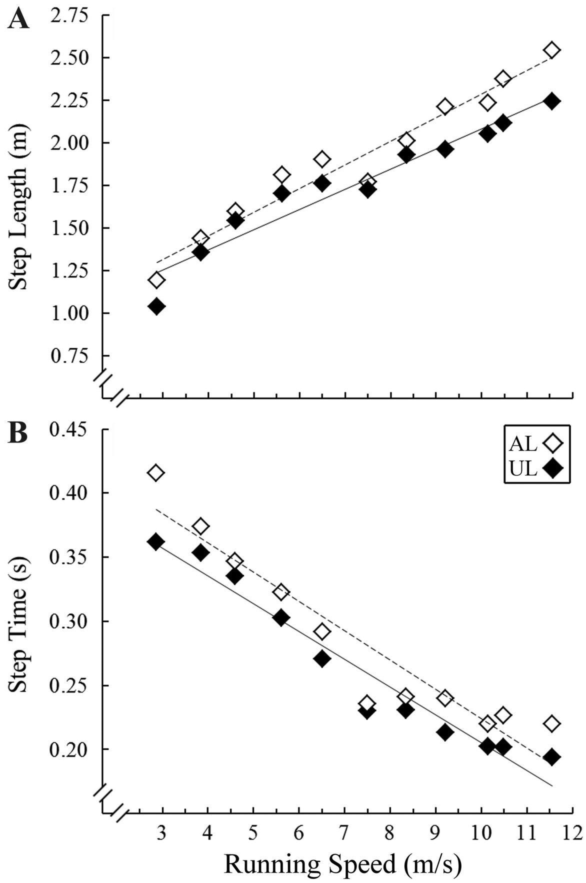

Fig. 2. Step length (L_{step}, *A*) and step time (t_{step}, *B*) for the affected leg (AL) and unaffected leg (UL) over the range of running speeds (v). Broken lines, AL regression lines; solid lines, UL regression lines. The following are the respective regression equations: AL $L_{step} = 0.14v + 0.90$; $R^2 = 0.95$; $P < 0.001$. UL $L_{step} = 0.12v + 0.90$; $R^2 = 0.93$; $P < 0.001$. AL $t_{step} = -0.023v + 0.453$, $R^2 = 0.90$; $P < 0.001$. UL $t_{step} = -0.022v + 0.423$; $R^2 = 0.95$; $P < 0.001$.

0.95; $P < 0.001$), and UL F_{avg} increased 10% ($P = 0.001$) (Fig. 3 and Table 1). Over the speed range, AL peak braking GRF increased 230% ($y = -0.025x + 0.014$; $R^2 = 0.90$; $P < 0.001$), UL peak braking GRF increased 466% ($y = -0.082x - 0.021$; $R^2 = 0.83$; $P < 0.001$), and AL peak propulsive GRF increased 183% ($y = 0.044x + 0.166$; $R^2 = 0.82$; $P < 0.001$) (Table 1). Running speed did not affect AL F_{avg} ($P = 0.676$) (Fig. 3 and Table 1) or UL peak propulsive GRF ($P = 0.943$) (Table 1).

From 2.87 to 11.55 m/s, AL peak vertical GRF increased 17% ($y = 0.05x + 2.68$; $R^2 = 0.60$; $P = 0.005$) and UL peak vertical GRF increased 16% ($y = 0.10x + 3.11$; $R^2 = 0.79$; $P < 0.001$) (Table 1). Across running speeds, peak AL ($y = -0.006x + 0.081$; $R^2 = 0.90$; $P < 0.001$) and UL ($y = -0.007x + 0.091$; $R^2 = 0.89$; $P < 0.001$) Δy decreased 76 and 69%, respectively, due in part to a 110% increased AL θ ($y = 0.027x + 0.217$; $R^2 = 0.94$; $P < 0.001$) and 96% increased UL θ ($y = 0.026x + 0.239$; $R^2 = 0.91$; $P < 0.001$). Furthermore, from 2.87 to 11.55 m/s, AL ($y = 0.003x + 0.107$; $R^2 = 0.42$; $P = 0.030$) and UL ($y = 0.004x + 0.116$; $R^2 = 0.65$; $P = 0.003$) ΔL increased 28 and 38%, respectively. k_{AL} ($P = 0.569$) and k_{UL} ($P = 0.941$) were independent of running speed (Table 1). Moreover, the only variables that were similar between the AL and UL across running speeds were peak propulsive GRF ($P = 0.345$) and θ ($P = 0.224$).

DISCUSSION

The purpose of this case study was to quantify the spatiotemporal, GRF, and spring-mass model parameters of the fastest athlete with a unilateral transtibial amputation across running speeds. From 2.87 to 11.55 m/s, this athlete increased his AL and UL step lengths from 1.19 to 2.54 m and 1.03 to 2.24 m, respectively (Fig. 2). The longer AL steps at each speed coincide with previous research suggesting that athletes with unilateral transtibial amputations exhibit similar or longer steps with their AL compared with their UL (14, 15). Also, at similar speeds, the present study's athlete exhibited AL and UL step lengths that were both within 1SD of those elicited by six athletes with unilateral transtibial amputations at their top running speeds (8.75 ± 0.97 m/s) (14). Additionally, an accomplished athlete with bilateral transtibial amputations exhibited mean step lengths of 2.03 m at 10.0 m/s (22), which is similar to the mean UL step length (2.05 m) and shorter than the mean AL step length (2.23 m) of the present study's athlete at 10.14 m/s. For further comparison, nonamputees yield mean

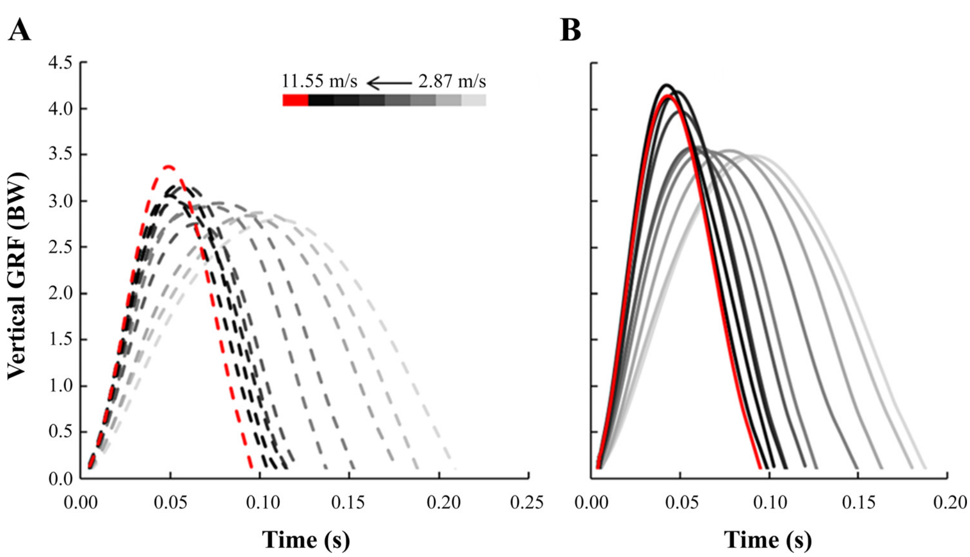

Fig. 3. Mean vertical ground reaction force (vGRF) traces from the AL (broken lines, *A*) and UL (solid lines, *B*) across running speeds (2.87–11.55 m/s). Light to dark vGRF lines indicate slower to faster running trials, with the fastest running trial in red. AL average vertical GRF (F_{avg}) was not statistically different across running speed ($P = 0.676$). The following is the regression equation: UL $F_{avg} = 0.03v + 1.88$; $R^2 = 0.72$; $P = 0.001$.

Table 1. *Mean elicited vGRFs and hGRFs across running speeds for the UL and AL*

	Peak vGRF		Stance Avg vGRF		Peak Braking hGRF		Peak Propulsive hGRF		Leg Stiffness, kN/m	
Running Speed, m/s	UL	AL	UL	AL	UL	AL	UL	AL	UL	AL
2.87	3.52	2.82	1.98	1.72	0.14	0.09	0.39	0.25	24.0	19.9
3.84	3.53	2.85	1.96	1.76	0.27	0.08	0.43	0.36	21.0	18.5
4.60	3.62	2.94	2.07	1.81	0.38	0.10	0.48	0.42	20.6	17.4
5.62	3.61	3.09	2.07	1.92	0.53	0.11	0.49	0.47	21.1	18.1
6.51	3.56	3.06	2.10	1.89	0.56	0.15	0.50	0.47	21.6	17.0
7.50	3.56	2.81	2.03	1.64	0.86	0.18	0.50	0.36	20.1	19.0
8.35	3.98	3.22	2.21	1.80	0.81	0.17	0.37	0.46	22.0	19.5
9.21	4.22	3.04	2.29	1.67	0.86	0.23	0.41	0.59	20.1	14.8
10.14	4.14	3.07	2.27	1.73	0.80	0.21	0.44	0.62	22.7	18.2
10.48	4.27	3.29	2.25	1.83	0.83	0.30	0.43	0.65	23.4	18.4
11.55	4.18	3.39	2.17	1.76	0.82	0.28	0.46	0.70	21.2	18.6

vGRF, vertical ground reaction forces; hGRF, horizontal ground reaction forces; UL, unaffected leg; AL, affected leg. All forces are presented in units of body weight. UL and AL peak vGRF ($P \leq 0.005$), UL stance average (Avg) vGRF ($P < 0.001$), AL and UL peak braking hGRF ($P < 0.001$), and AL peak propulsive hGRF ($P < 0.001$) correlated with running speed. AL stance Avg vGRF ($P = 0.676$) and UL peak propulsive hGRF ($P = 0.943$) were independent of running speed.

(±SD) step lengths of 2.04 m at 9.20 ± 0.59 m/s (23), 2.11 m at 9.25 ± 0.37 m/s (24), and 2.37 m at 10.0 ± 0.0 m/s (22). Therefore, athletes with unilateral, bilateral, and without transtibial amputations achieve fast running speeds using different spatiotemporal variable magnitudes.

Stance average vertical GRF relative to body weight, a key determinant of step length, generally increases with faster running speeds (2, 10, 23, 24). However, this study and others have presented representative data showing that at certain speed increments, athletes with and without amputations naturally increase running speed (e.g., 6.51–7.50 m/s; Fig. 2) by decreasing their stance average vertical GRFs and considerably reducing their step times (2, 10) (Fig. 3). Thus, at these speed increments, athletes run faster by using shorter step lengths and much briefer step durations than those of the preceding slower speed. This can happen because running speed is determined from the combination of contact length, stance average vertical GRF relative to body weight, and step time (23).

The present study's athlete's AL stance average vertical GRFs and AL step lengths were lower and longer than those of his UL at each speed, respectively. Even though he exhibited longer AL contact lengths, based on *Eq. 2* we would predict this athlete to exhibit shorter, not longer, AL vs. UL step lengths. Perhaps this phenomenon is related to the athlete's leg length discrepancy (the AL was 6 cm taller than the UL). For instance, AL CoM height was 5.9 ± 1.3 cm taller at initial ground contact compared with UL height across speeds (paired 2-tailed *t*-test; $P < 0.001$). Conceivably, his AL stance average vertical GRFs were lower and AL step lengths were longer than those of his UL because of the net lowering of the CoM through the AL step and the net raising of the CoM through the UL step. This notion is supported by the longer aerial times following the AL vs. UL steps (14) (Fig. 1) and by our previous study (3), which found that decreased prosthetic height elicited more symmetric stance average vertical GRFs during running at 2.5 and 3.0 m/s for athletes with unilateral transtibial amputations.

The results of the present study indicate that athletes with unilateral transtibial amputations can achieve elite top speeds (i.e., >10 m/s) while eliciting different spatiotemporal, GRF, and spring-mass model characteristics than those of athletes with bilateral and without transtibial amputations. The present study's dataset may be implemented in future studies that compare the sprinting abilities of athletes with unilateral transtibial amputations with those of athletes with different amputation statuses. Furthermore, this investigation may be used for the development of future RSP and socket designs by providing insight into the demands placed on these devices during running. Typically, k_{AL} of athletes with transtibial amputations decreases with faster running speeds (2, 19), which contrasts the results of the present study's athlete who maintained constant k_{AL} across running speeds. Perhaps, athletes with unilateral transtibial amputations need to maintain and not decrease k_{AL} to achieve faster top speeds. Athletes with transtibial amputations may be able to maintain constant k_{AL} by using different RSP configurations (1) or altering RSP/leg segment geometry during running (13). Additionally, the present study's athlete exhibited more asymmetric spatiotemporal variables and GRFs than those of nonamputees at matched running speeds. For example, at 9.5 ± 0.42 m/s, nonamputees exhibit average step length and stance average vertical GRF asymmetries of 1.7 ± 3.2 and 2.0 ± 4.5% (±SD), respectively (16), whereas at 9.21 m/s, the present study's athlete exhibited step length and stance average vertical GRF asymmetries of 11.9 and 31.4%, respectively. Currently, it is unknown whether biomechanical asymmetries limit the top speed of athletes with unilateral transtibial amputations. Moreover, although treadmill and overground running are biomechanically similar (9), athletes only need to overcome minimal air resistance during treadmill running because of arm and leg swing (11). Hence, athletes can theoretically attain faster running speeds on a treadmill than overground.

Conclusions. We present spatiotemporal, GRF, and spring-mass model variables of the fastest athlete with a unilateral transtibial amputation while running at 2.87–11.55 m/s. In general, his AL spatiotemporal variables coincide with those of nonamputee sprinters, whereas his AL stance average vertical GRFs better match those from of an athlete with bilateral transtibial amputations. In contrast, the UL spatiotemporal variables of the athlete in the present study coincide with those elicited by an athlete with bilateral transtibial amputations, whereas the present study's athlete's UL stance average vertical GRFs better match those exhibited by nonamputees. Furthermore, the present study's athlete maintained constant k_{leg} in both legs across running speeds, which is like that of nonamputees and dissimilar to that of athletes with transtibial amputations. In addition to these comparisons, this study provides insight regarding how the fastest athlete with a unilateral transtibial amputation using an RSP adapts his biomechanics to achieve elite running speeds.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

O.N.B. and A.M.G. conceived and designed research; O.N.B. and A.M.G. performed experiments; O.N.B. and A.M.G. analyzed data; O.N.B. and A.M.G. interpreted results of experiments; O.N.B. and A.M.G. prepared figures; O.N.B. and A.M.G. drafted manuscript; O.N.B. and A.M.G. edited and revised manuscript; O.N.B. and A.M.G. approved final version of manuscript.

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