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Point:Counterpoint

"Artificial limbs do / do not make artificially fast running speeds possible"

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Peter G. Weyand and Matthew W. Bundle

COUNTERPOINT: ARTIFICIAL LIMBS DO NOT MAKE ARTIFICIALLY FAST RUNNING SPEEDS POSSIBLE

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POINT: ARTIFICIAL LIMBS DO MAKE ARTIFICIALLY FAST RUNNING SPEEDS POSSIBLE

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Overview: Three mechanical variables constrain the speeds of human runners: 1) how quickly the limbs can be repositioned for successive steps, 2) the forward distance the body travels while the foot is in contact with the ground, and 3) how much force the limbs can apply to the ground in relation to the body's weight. Artificially increasing one or more of these variables beyond the limits imposed by human biology would artificially enhance running speeds.

Mechanics of running: The classical literature on terrestrial locomotion established that level running is mechanically analogous to a ball bouncing forward along the ground (3, 4). Like a bouncing ball, a runner's mechanical energy and forward momentum are conserved via recurring exchanges of kinetic and potential energy during travel. Runners accomplish this by using their legs in a spring-like manner to bounce off the ground with each step (3, 4, 5, 6, 7). On landing strain energy is stored as the body's weight and forward speed compress the stance limb and forcibly lengthen muscles and tendons. The strain energy stored upon landing is subsequently released via elastic recoil as the limb extends to lift and accelerate the body back into the air prior to take-off. The conservation of mechanical energy and forward momentum minimizes the need for propulsive force and the input of additional mechanical energy once a runner is up to speed (9). Thus, contrary to intuition, the primary mechanical requirement of running is applying ground support forces large enough to provide the aerial time needed to reposition the swing limb for the next step (9, 10, 11, 13).

Under steady-speed, level-running conditions, the average vertical force applied to the ground over the course of the stride must equal the body's weight (W_b; Figure 1).

The instantaneous vertical forces across successive contact (t_c), and aerial (t_{aer}) periods of a representative sprint running stride are illustrated in Figure 1. Note that each stride consists of the contact plus swing period (t_{sw}) of the same limb ($t_{str} = t_c + t_{sw}$) and two consecutive steps (where: $t_{step} = t_c + t_{aer}$).

Gait mechanics and speed: Because the height of the body is nearly the same at landing and take-off, the average vertical force applied during foot-ground contact (F_{avg}), when expressed as a multiple of the body's weight (F_{avg}/F_{Wb}), can be determined from the ratio of the total step time (t_{step}) to the contact time ($F_{avg} = t_{step}/t_c$). Thus, forward speed can be accurately (11) expressed as:

$$\text{Speed} = \text{Freq}_{step} \bullet L_c \bullet F_{avg} \qquad \text{(eq. 1)}$$

where forward speed is in m/s, Freq_{step} ($1/t_{step}$) is the number of steps per second in s^{-1}, L_c is the forward distance traveled during the contact period in meters, and F_{avg} is the average vertical force applied during contact expressed as a multiple of the body's weight.

Here, we compared the running mechanics of a double amputee sprint runner who runs with bilateral, transtibial, carbon fiber prostheses to: 1) four intact-limb track athletes with the same top speed tested under the same laboratory conditions, and 2) two elite male sprinters during overground running.

Artificial limbs and performance: The stride frequencies attained by our double amputee sprint subject at his top speed were greater than any previously recorded during human sprint running that we are aware of. They were 15.8% greater than those of the intact-limb athletes (13) tested in the laboratory (2.56 vs. 2.21 [0.08] s^{-1}), and 9.3% greater than those of elite sprinters (8) running at 11.6 m/s overground (2.34 [0.13] s^{-1}). The extreme stride frequencies of our amputee subject were the direct result of how rapidly he was able to reposition his limbs. His swing times at top speed (0.284 s) were 21% shorter than those of the athletes tested in the laboratory (0.359 [0.019] s) and 17.4% shorter than the first two finishers (0.344 s) in the 100 m dash at the 1987 World Track and Field Championships (8). We consider stride and step frequencies nearly 10% greater than those measured for two of the fastest individuals in recorded human history to be artificial and clearly attributable to a non-biological factor: the mass of our amputee subject's artificial lower limbs is less than half that of fully biological lower limbs (1).

Our amputee subject's contact lengths at top speed in relation to his standing leg length (L_o) and height were also advantageous for speed. The contact length to leg length ratio of our amputee subject was 9.6% greater (1.14 vs. 1.04 [0.08]) than those of the track athletes (13) tested in the laboratory; his contact length to height ratio was 16.2% greater (0.62 vs. 0.53) than those of the elite sprinters measured on the track (8). We attribute our amputee subject's long contact lengths and times (13) to the relatively greater compliance of his artificial limbs.

The combined effects of lightweight, compliant artificial limbs: minimum swing times of extreme brevity, and moderately prolonged ground contact lengths is to substantially reduce the stance-averaged vertical forces required to run at any given speed

(Figure 1). Our amputee subject's stance-averaged vertical force at top speed was 0.46 W_b lower than the values measured for male track athletes (13) at the same top speed (1.87 vs. 2.30 [0.13] W_b). However, in contrast to his extreme swing times and relatively long contact lengths, the ground forces he applied were typical (11), falling well within the range of values reported (1.65-2.52 W_b) for a heterogeneous group of active subjects with intact limbs (top speed range: 6.8-11.1 m/s) that included two accomplished male sprinters.

From top speed to sprinting performance: A quantitative assessment of the performance advantage provided by the artificial limbs of our amputee subject can be made simply by adjusting his swing times and contact lengths to typical values for male track athletes with intact limbs (13) and examining the effect on his top sprinting speed using eq. 1. Using the swing time of 0.359 s measured for the intact-limb track athletes in the laboratory, a contact length of 1.05 m adjusted to equal the L_c/L_o ratio of the intact-limb track athletes in conjunction with his measured F_{avg} (1.84 Wb) and t_c values (0.107 s) decreases his top speed from the 10.8 m/s observed to 8.3 m/s.

Because top speeds can be used to predict 200 and 400 m run times to within 3.5% or less (3, 12) for both intact-limb runners (3, 12) and this amputee subject (13), we can also quantify the performance advantage provided by artificial vs. intact limbs in specific track events. The reduction of our amputee subject's top speed from 10.8 to 8.3 m/s, in conjunction with his measured velocity at VO_{2max} at the time of his laboratory testing (5.0 m/s), increases his running-start 200 m time by nearly 6 s (from 21.6 to 27.3 s), and his running-start 400 m time by nearly 12 s (from 49.8 to 61.7 s).

Conclusion: Our analysis identifies two modifications of existing lower limb prostheses that would further enhance speed for double transtibial amputees: reduced mass to further decrease minimum swing times and increased length to further increase contact lengths.

We conclude that the moment in athletic history when engineered limbs outperform biological limbs has already passed.

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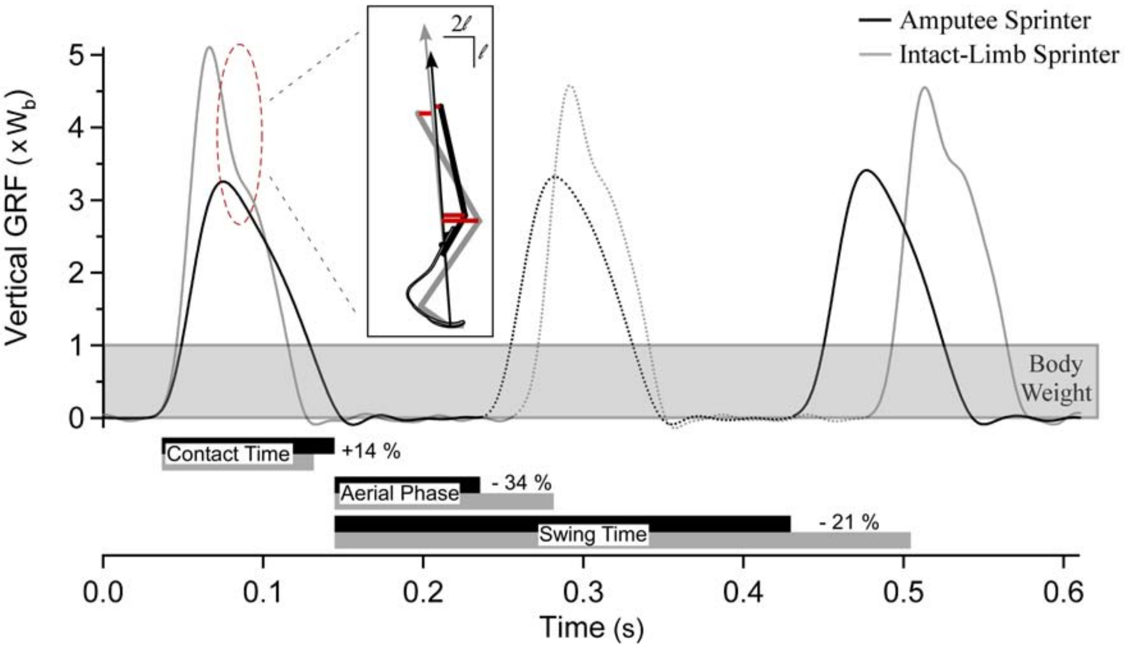
Figure Captions

Fig. 1. Vertical ground reaction forces, normalized to body weight *vs.* time for our amputee sprinter (black) and an intact-limb sprinter (gray) at a treadmill speed of 10.5 m/s; shaded region indicates an average force of 1 body weight. Horizontal bars denote the stride-phase durations, and percent differences, between the amputee subject and intact limb norms (*n* = 4; ref 13). *Leg compression inset*: at mid-stance when limb compression is at or near maximum, the external moment arms at the knee and hip (distance between the joint centers and the GRF) are 40 and 65% less, respectively, for our amputee subject compared to a group (*n* = 5) of intact-limb sprinters (data from ref 1; note: the horizontal scale has been doubled for the purpose of illustration).


Amputee Sprinter
Intact-Limb Sprinter
Vertical GRF (x W$_b$)
5
4
3
2
1
0
2ℓ
ℓ
Body Weight
Contact Time
+14 %
Aerial Phase
- 34 %
Swing Time
- 21 %
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Time (s)

Counterpoint:

Artificial legs do not make artificially fast running speeds possible

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"Extraordinary claims require extraordinary evidence" Carl Sagan

There is insufficient evidence to conclude that modern running specific prostheses (RSP) provide physiological or biomechanical advantages over biological legs. A grand total of n=7 metabolic running economy values for amputees using RSP have been published (1,13). Even worse, ground reaction force (GRF) and leg swing time data at sprint speeds exist for only one amputee, Oscar Pistorius (2,13). Until recently it would have been preposterous to consider prosthetic limbs to be advantageous, thus, the burden of proof is on those who claim that RSP are advantageous. Here, we conservatively presume neither advantage nor disadvantage as we weigh and discuss recently published scientific data. Further, we propose a series of experiments that are needed to resolve the topic of this debate.

RSP do not provide a distinct advantage or disadvantage in terms of the rates of oxygen consumption at sub-maximal running speeds (running economy, RE). Brown et al. (1) compared the RE of six transtibial amputee runners (5 unilateral and 1 bilateral) to six age- and fitness-matched non-amputee runners. The mean RE was numerically worse for the amputees using RSP across all speeds (219.5 vs. 202.2 $mlO_2/kg/km$), but the difference did not reach the criterion of significance ($p < 0.05$). The bilateral transtibial amputee from Brown et al. had a mean RE of 216.5 $ml\ O_2/kg/km$. The only other reported RE value for a bilateral amputee is that for Oscar Pistorius, 174.9 $mlO_2/kg/km$ (13). For good recreational runners (n=16), Morgan et al. (9) reported a mean [SD] RE value of 190.5 [13.6] $mlO_2/kg/km$. Thus, the Brown et al. bilateral amputee's RE was 1.92 SD above that mean and Pistorius' RE was 1.15 SD below that mean. Both athletes use the same type of prostheses. From this scant evidence, it would be foolhardy to conclude that RSP provide a metabolic advantage or disadvantage.
Since vertical GRF is the primary determinant of maximal running speed (11,12), GRF data for amputee runners are critical to this debate. Although previous studies have characterized some aspects of the biomechanics of amputee running and sprinting (3,4,6,7,8,15), there are no published GRF data for unilateral amputees at their top running speeds. GRF data for top speed running have been published for only one bilateral amputee, Oscar Pistorius. To claim that prosthetic legs provide a mechanical advantage over biological legs based upon n=1 is inherently unscientific and we are surprised that any scientists would make such a claim.

Both Brüggemann et al. (2) and Weyand et al. (13) found that Pistorius exerts lower vertical GRFs than performance matched non-amputees. Brüggemann et al. contorted this force deficiency into a supposed advantage, claiming that the smaller vertical forces and impulse allow Pistorius to perform less mechanical work than his peers. That reasoning fails to recognize that sprinting requires maximizing force and mechanical power output, not minimizing them. In their seminal work, Weyand et al. (12) concluded that "human runners reach faster top speeds … by applying greater support forces to the ground". Thus, it is enigmatic that Weyand and Bundle (14) in this debate can convolute the smaller GRF exerted by Pistorius into a purported advantage.

Two factors may be responsible for the GRF deficit that Pistorius exhibits: 1. his passive, elastic prostheses (and/or their interface with the residual limb) prevent him from generating high forces and/or 2. his legs are not able to generate high ground force due to relative weakness. Factor 1 is certainly plausible. Compliant prostheses are necessary for running because the forces on the residual limb-prosthesis socket interface would otherwise be intolerable. Despite the compliance of RSP, amputees uniformly report significant pain at the interface during running. Factor 2 is also possible, though Pistorius has been active and engaged in various sports for 20+ years (10). He may have learned to compensate for his force impairment by training his body to use other mechanical means to achieve fast speeds.

Although Weyand et al. (12) stated “more rapid repositioning of limbs contributes little to the faster top speeds of swifter runners”, Weyand and Bundle (14) argue that Pistorius is able to run fast because his lightweight prostheses allow him to rapidly reposition his legs during the swing phase. Brief leg swing times increase the fraction of a stride that a leg is in contact with the ground and thus reduce the vertical impulse requirement for the contact phase. But, the notion that lightweight prostheses are the only reason for Pistorius’ rapid swing times ignores that he has had many years to train and adapt his neuromuscular system to using prostheses. Weyand and Bundle (14) argue that lightweight prostheses allow Pistorius to run faster than he should for his innate strength/ability to exert vertical GRFs. An equally plausible hypothesis is that he has adopted rapid leg swing times to compensate for the force limitations imposed by his prostheses.

Pistorius’ leg swing times are not unreasonably or unnaturally fast. Non-elite runners have mean [SD] minimum leg swing times of 0.373 [0.03] sec (12). Pistorius’ leg swing time of 0.284 sec at 10.8 m/s is nearly 3 SD faster than that mean. However, leg swing times as low as 0.31 sec for Olympic 100m medalists at top speed have been reported (12). If elite sprinters have similar variation in leg swing times, then a leg swing time of 0.284 sec is not aberrant. Further, recreational athletes sprinting along small radius (1m) circular paths exhibited mean leg swing times of just 0.234 sec (5). It appears that when faced with stringent force constraints, runners with biological legs choose very short leg swing times. A thorough study of leg swing times for elite Olympic and Paralympic sprinters could provide further perspective.

Fortunately, there are simple experiments with testable hypotheses that can resolve many of the issues presented here. We propose a comprehensive biomechanical study of high-speed running by elite, unilateral amputee athletes. Studying unilateral amputees would allow direct comparisons between their affected and unaffected legs. First, we hypothesize that unilateral amputee sprinters exert greater vertical GRFs with their unaffected leg than with their affected leg. If that hypothesis is supported by data, it would indicate that RSP impose a force limitation and are thus disadvantageous. Second, we hypothesize that unilateral amputee sprinters run with equally rapid leg swing times for their affected and unaffected legs. If that hypothesis is supported, it would dispel the idea that lightweight prostheses provide a leg swing time advantage. Third, we hypothesize that adding mass to the lightweight RSP of unilateral and bilateral amputees will not increase their leg swing times or decrease their maximum running speeds. If that hypothesis is supported, then the assertion that the low inertia of RSPs provide an unnatural advantage would be discredited. Given that some Paralympic sprinters choose to add mass to their prostheses, we anticipate that added mass will not significantly slow leg swing times. Future experiments should also quantify how RSPs affect accelerations and curve running. Both require greater force and power outputs than straight-ahead steady speed running. We hope that the data needed to test these hypotheses will be forthcoming so that this debate can be elevated from a discussion of what might be to a discussion of what is known.

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REBUTTAL

Point: Artificial limbs do make artificial running speeds possible

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We agree with our counterpoint colleagues that minimum leg repositioning, or swing times and mass-specific ground reaction forces are critical determinants of sprint running performance.

Swing times: biologically normal or artificially brief? Our conclusion that the artificial-limb swing times (0.284 s) observed at top speed are artificially brief is based on the well-established practice of evaluating single observations vs. a comparison sample population's mean and variance with a threshold of > 3.0 standard deviation (SD) units (7) for identifying outliers. In comparison to: the largest intact-limb reference population (9) available of 33 active subjects (mean [SD] = 0.373 [0.026] s), four performance-matched track athletes (10) during treadmill running (0.359 [0.019] s), and thirteen elite, male 100-meter sprinters (6, 8, 9) in competition (0.329 [0.015] s), the artificial-limb value is -3.42, -3.95 and -3.00 SD units below these three respective means. The elite population includes individuals with the most extreme gait adaptations for speed in recorded human history.

The artificial-limb value is also -1.7 and -2.2 active and elite population SD units, respectively, below the single lowest intact-limb swing time (9) ever published (0.317 s), and 16.6% shorter than the mean of the six former 100-meter, world-record holders (0.339 s) in the elite sample above. The artificial-limb value under consideration is not simply an outlier; it is quite literally off the biological charts.

The evidence offered for the competing conclusion (5) that the artificial-limb value is not unnaturally fast is: 1) an invalid comparison (3) to running slowly (2.99 m/s) in a two-meter diameter circle, and 2) the incorrect suggestion that the artificial-limb value might fall <1.0 elite SD unit from the single lowest biological value published, when as noted previously, the actual difference is -2.2.

Reduced force requirements for speed. Given that the stride-averaged vertical force must equal the body's weight, lesser ground support forces at the same speeds should not be interpreted as a limb strength deficiency, but here (Fig. 1) represent the inevitable physical consequence (4) of ground contact times lengthened, and aerial times shortened by artificially compliant and lightweight (2) lower limbs. Our double amputee subject "bounces" on his compliant, artificial lower limbs while holding his upper biological limbs relatively straight (2; inset Fig. 1). More erect limb posture and reduced ground force requirements (1) co-reduce the muscular forces required to attain the same sprint running speeds to less than half of intact-limb levels.

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REBUTTAL

Counterpoint: Artificial limbs <u>do not</u> make artificial running speeds possible

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"You cannot be serious!" John McEnroe

Weyand and Bundle's "calculation" (4) that modern passive prostheses provide a 12 second advantage over 400m is absurd and insulting to Paralympic athletes. Nearly any schoolboy athlete can run 400m under 60 seconds. Every year, thousands of athletes run under 50 seconds, yet only one amputee has ever broken 50 seconds. Would Weyand and Bundle predict that the world record holder, Michael Johnson, would run 31 seconds if he had both legs amputated?

We reject Weyand and Bundle's (4) assertion that lightweight prostheses facilitate unnaturally rapid leg swing times that reduce the force required for amputee runners to run as fast as non-amputees. Rather than being beneficial, a recent study of six, unilateral, amputee sprinters demonstrated that prosthetic legs impair force production (2). At top speed, the stance average vertical force exerted by the affected leg (AL) was 9% less than for the unaffected leg (UL) ($P < 0.0001$). Recall that Weyand et al. (3) emphasized that vertical force generation is the primary determinant of top speed. Thus, running-specific prostheses likely limit the top speeds of amputee sprinters. Impaired force generation also likely impacts acceleration and curve running performance (1).

Several lines of evidence (2) show that the leg swing times (t_{sw}) used by amputee sprinters are not unnaturally fast. Video analysis of the 2008 Paralympic Games revealed that the 1st place bilateral amputee's mean t_{sw} was 0.302 ±SE 0.003s in the 100m and 0.318 ± 0.003s in the 200m. The 2nd place finisher in the 200m was a unilateral amputee with equally rapid average t_{sw} of 0.304 ± 0.005s for his UL and 0.323 ± 0.004s for his AL. Thus, the unilateral amputee runner swings his natural leg as fast or faster than either his or the bilateral amputee's lightweight artificial legs. Video analysis of the 2008 Olympic 100m revealed mean t_{sw} of 0.328, 0.305 and 0.274s for the first three finishers. Thus, the t_{sw} of Paralympic sprint medalists were quite similar to those of their Olympic cohorts.

Based on substantial data rather than conjecture, we conclude that lower-limb amputation and modern running prostheses do not facilitate unnaturally fast leg swing times or fast running speeds. It is common sense that amputation and prosthetic legs impair force generation. Rapid leg swing times can result from learning and training but can only partially compensate for the force impairment incurred by current, passive-elastic running prostheses.

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