any given speed (Fig. 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 W_b) 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 $\dot{V}O_{2max}$ 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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COUNTERPOINT: ARTIFICIAL LEGS DO NOT MAKE ARTIFICIALLY FAST RUNNING SPEEDS POSSIBLE

"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. Furthermore, 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 submaximal 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 nonamputee runners. The mean RE was numerically worse for the amputees using RSP across all speeds (219.5 vs. 202.2 ml $O_2 \cdot kg^{-1} \cdot km^{-1}$), 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 $O_2 \cdot kg^{-1} \cdot km^{-1}$. The only other reported RE value for a bilateral amputee is that for Oscar Pistorius, 174.9 ml $O_2 \cdot kg^{-1} \cdot km^{-1}$ (13). For good recreational runners ($n = 16$), Morgan et al. (9) reported a mean (SD) RE value of 190.5 (13.6) ml $O_2 \cdot kg^{-1} \cdot km^{-1}$. 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, 6–8, 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 on $n = 1$ 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 nonamputees. 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, although 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. Nonelite runners have mean (SD) minimum leg swing times of 0.373 (0.03) s (12). Pistorius' leg swing time of 0.284 s at 10.8 m/s is nearly 3 SD faster than that mean. However, leg swing times as low as 0.31 s for Olympic 100-m 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 s is not aberrant. Furthermore, recreational athletes sprinting along small radius (1 m) circular paths exhibited mean leg swing times of just 0.234 s (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 FROM WEYAND AND BUNDLE

We agree 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 bilateral artificial limb swing time (0.284 s) measured at top speed (10) is 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 deviations (SD) for identifying outliers (7). In comparison to an intact-limb reference population (9) of 33 active, treadmill-tested subjects [mean (SD) = 0.373 (0.026) s]; four performance-matched track athletes (10) during treadmill running [0.359 (0.019) s]; and 22 male, world-class, 100-m sprinters (6, 8) in competition [0.330 (0.014) s]; the double-artificial-limb value is −3.4, −4.0, and −3.3 SD units below these three respective means. It is also 15.7% shorter than the mean of the five former 100-m world-record holders (0.337 s) in the competition sample.

Even in comparison to individuals with the most extreme gait adaptations for speed in recorded human history, the double-artificial-limb value is not simply an outlier; it is quite literally off the biological charts.

Our colleagues recently published (4) conclusion that the double-artificial-limb value is not artificially brief is not supported by the data we have published with them (10) or the valid data from field (6, 8) and laboratory (9, 10) settings analyzed above. Instead, television footage of Olympic races acquired for entertainment purposes is cited (4). Low shutter speeds, frame rates (30 Hz), wide fields of view, and force-video offsets (9) make television-estimated swing times highly uncertain. For example, the swing time of the one Olympian purportedly more brief (0.274 ± 0.004 s; Ref. 4) than the double-amputee value, is actually 16.2% greater (0.318, 0.318, and 0.320 s) when measured using research-quality, high-speed, motion-capture techniques (6).

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 (3) 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 lower limbs while holding his upper biological limbs relatively straight (2; Fig. 1, *inset*). More erect limb posture (1) and reduced ground force requirements co-reduce the muscular forces required to attain the same sprint running speeds to less than one-half of intact limb levels.

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REBUTTAL FROM KRAM, GRABOWSKI, MCGOWAN, BROWN, MCDERMOTT, BEALE, AND HERR

"You cannot be serious!"—John McEnroe

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