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Comments on Point:Counterpoint: Artificial limbs do/do not make artificially fast running speeds possible

TO THE EDITOR: Weyand and Bundle (4) argue that artificial limbs can enable artificially fast running. Their argument, however, is based on single-speed running in a single bilateral-amputee athlete and should therefore be treated with caution (2).

A runner and prosthesis comprise a mass-spring system with nearly constant natural frequency (5). If the prosthesis has high stiffness, the system has a high frequency and a short period. If it has low stiffness, the system has a low frequency and a long period. In the first quarter period, kinetic energy is stored as elastic energy in the carbon fiber keel. In the second quarter period, this elastic energy is returned as kinetic energy. Optimal contact time is therefore one-half the natural period of the system.

Ground contact time is determined by a runner's speed and leg compliance (1), with the actual contact time matching the optimal time at only one speed. This was probably the speed studied by Weyand and Bundle. At other speeds, an amputee is at a disadvantage because energy is returned from the prosthesis at the wrong instant in the cycle (3).

Nevertheless, Weyand and Bundle show that, at the optimal speed, a bilateral amputee achieves higher ground contact times and lower swing times than able-body athletes (4). The amputee can therefore apply forces to the ground for a higher proportion of the cycle and can increase the force that propels him forward. Increasing the length of a prosthesis (4), however, would likely increase the backward force experienced during the first stages of ground contact, requiring compensation elsewhere in the cycle.

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TO THE EDITOR: At high running speeds, a large fraction of the power developed each step during the push appears to be sustained by elastic energy stored within muscle-tendon units during the brake (3). Elastic storage and recovery is improved at high speeds by privileging the role of tendon relative to muscle at the expense of a high muscle activation (1). Replacing muscle-tendon units with a passive, inexpensive, elastic structure may result in more efficient elastic rebound by increasing the power developed at low cost during the push.

At low running speeds, the step frequency f is advantageously tuned to the resonant frequency of the bouncing system fs (4). With increasing running speed, f increases less than fs to contain the power spent to reset the limbs at each step (1). If the half period of the bouncing system is measured in Fig. 1 of Weyand and Bundle (6), as the time where the vertical force exceeds body weight (2), the resonant frequency fs of the bouncing system results ~60% greater than the step frequency f in the intact-limb subject and ~30% greater in the amputee. If this is confirmed by measuring f and fs at different running speeds, the advantage of a reduced mass of the lower limb may be considered.

These two observations favor the hypothesis that artificial limbs may make artificially fast running speeds possible, even if, as stated by Kram et al. (5), this hypothesis cannot be statistically proven.

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"NET ADVANTAGE" IS MORE ROOTED IN SPORT THAN SCIENCE

TO THE EDITOR: I propose that "net advantage" is a poorly defined experimental metric, more rooted in sport than science. Although artificially faster running is theoretically possible, current scientific evidence seems insufficient to prove a net advantage for running prostheses. To scientifically demonstrate a net advantage requires knowledge, precise measurement, and weighting of all interdependent biomechanical factors contributing to speed. Experimental variability, measurement inaccuracy, and task specificity further complicate the issue.

In addressing this question of net advantage, I believe both sides have interpreted and applied results beyond the intended scopes of the original scientific studies. One major concern is using statistically correlated kinetic and kinematic trends (2, 3) as a surrogate for a fundamental mechanistic understanding of speed limitations. Interpreting amputee mechanics in the context of how able-bodied runners achieve top speed makes

implicit assumptions that ignore biomechanical and neuromuscular differences.

Weyand and Bundle (3) estimate a 12-s prosthetic advantage by normalizing contact length and swing time to able-bodied gait. However, this simplification neglects neuromuscular adaptation and lacks experimental validation and mechanistic basis. Faster leg swing may provide certain advantages, but other factors may mitigate a net advantage.

Kram et al. (2) extrapolate unilateral running mechanics to bilateral gait. However, contradictory swing time findings in literature (1, 4) suggest dissimilar gait adaptation between unilateral and bilateral amputees.

It is misleading to overgeneralize or overinterpret scientific results in the context of unscientific questions like net advantage. Instead we should embrace the scientific merit of these studies and use their shortcomings to motivate further investigation of well-defined, testable hypotheses.

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FOR FORWARD RUNNING, STUDY FORE-AFT FORCES

TO THE EDITOR: The evidence presented in this debate shows that cheetah feet enable "artificial running" (5); however, whether it is "artificially fast" remains inconclusive (4). Some double-amputee behaviors (e.g., swing time) do appear outside the intact range (5). But the measures discussed in this debate—including swing time, contact length, stride frequency, aerial time, vertical force, vertical work, and metabolic cost (1, 4, 5, 6) are only correlates of fast running in intact sprinters, not mechanisms describing bipedal speed capacity.

It is true that the primary requirement for running at steady speed is weight support (5), but the steady top speed in question is ultimately the result of a fore-aft ground force balance (3). Runners initially accelerate due to imbalanced forces favoring forward motion. Later they stop accelerating, which implies that forward and rearward forces have reached a balance. A likely explanation is that leg muscles are unable to propel the landing foot rearward beyond a certain relative speed, due to leg inertia and the force-velocity relationship of leg extensors. At a steady top speed, finite axial leg stiffness requires the stance leg to land ahead of the center-of-mass (2), ensuring periods of both rearward and forward horizontal forces, which describes directly the necessary fore-aft force balance.

Future studies should refocus on the mechanistic limitations of bipedal forward speed, as well as whether prostheses unnaturally decouple vertical and fore-aft forces, enable faster rearward foot motion, or otherwise raise the speed at which fore-aft forces balance. These and other directly speed-related, biomechanical differences can clarify any proposed mechanisms of artificially fast running.

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TO THE EDITOR: The present debate opposes coauthors of a recent study (4), with a narrow focus on swing time and vertical ground reaction force, the latter being known as an important mechanical parameter determining top running speed, but not the former, according to Weyand et al. (5). However, whether they both influence *overall* 400-m performance *on the field*, and how remains unknown, and makes any speculation such as that leading to the 12-s advantage (3) questionable. This also questions about the extent to which top-speed running kinematic measurements such as swing time parallel what runners actually do on the ground, a fortiori when limbs mass and moment of inertia are different. However interesting it is to fully understand the specific adaptations allowing double-amputee athletes to reach top running speeds close to those of able-bodied athletes, using single-individual to control group comparisons (3, 4) is restricting. And so is using 30-Hz television footage to estimate and discuss swing times as short as ~300 ms (1, 2), which leads to measurement errors of ~10%, i.e., about one-half of the artificial/biological differences discussed here. Last, the whole formulation of this Point:Counterpoint is actually misleading: it would have been more consistent with the data/arguments presented to title "Artificial limbs do/do not [. . .] *in Oscar Pistorius.*" That said, it is an opportune start for experimental protocols specifically designed to answer the general question asked here as to whether artificial limbs have come to a point were they outperform biological ones.

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