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

POINT: ARTIFICIAL LIMBS DO MAKE ARTIFICIALLY FAST RUNNING SPEEDS POSSIBLE

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 springlike manner to bounce off the ground with each step (3–7). 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 on 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 (9–11, 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; Fig. 1). The instantaneous vertical forces across successive contact (t_c) and aerial (t_{aer}) periods of a representative sprint running stride are illustrated in Fig. 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: Speed = $Freq_{step} \cdot L_c \cdot F_{avg}$ (*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.

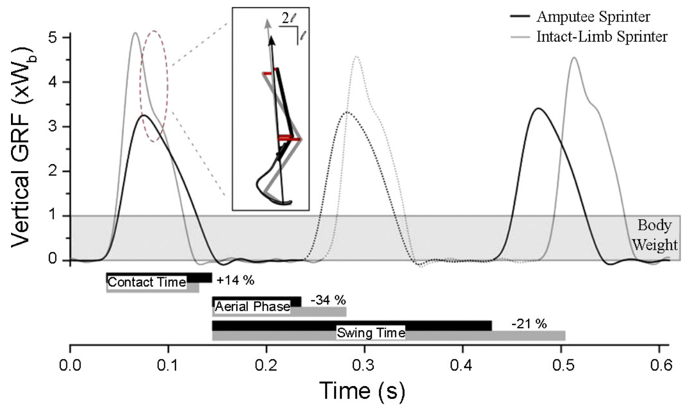

Fig. 1. Vertical ground reaction forces, normalized to body weight vs. time for our amputee sprinter (black) and an intact-limb sprinter (gray) at a treadmill speed of 10.5 m/s; shaded region indicates an average force of 1 body weight. Horizontal bars denote the stride-phase durations, and percent differences, 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 ground reaction force (GRF)] are 40 and 65% less, respectively, for our amputee subject compared with a group (n = 5) of intact-limb sprinters (data from Ref. 1; note: the horizontal scale has been doubled for the purpose of illustration).

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 of which we are aware. 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 nonbiological factor: the mass of our amputee subject's artificial lower limbs is less than one-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 (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.