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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

Peter G. Weyand and Matthew W. Bundle

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

Rodger Kram, Alena M. Grabowski, Craig P. McGowan, Mary Beth Brown, William J. McDermott, Matthew T. Beale & Hugh M. Herr

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POINT: ARTIFICIAL LIMBS DO MAKE ARTIFICIALLY FAST RUNNING SPEEDS POSSIBLE

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

88

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

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

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

109

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

115

$$116 \quad \text{Speed} = \text{Freq}_{\text{step}} \cdot L_c \cdot F_{\text{avg}} \quad (\text{eq. 1})$$

117

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

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

126

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

140 Our amputee subject's contact lengths at top speed in relation to his standing leg
141 length (L_0) and height were also advantageous for speed. The contact length to leg length
142 ratio of our amputee subject was 9.6% greater (1.14 vs. 1.04 [0.08]) than those of the
143 track athletes (13) tested in the laboratory; his contact length to height ratio was 16.2%
144 greater (0.62 vs. 0.53) than those of the elite sprinters measured on the track (8). We
145 attribute our amputee subject's long contact lengths and times (13) to the relatively
146 greater compliance of his artificial limbs.

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

150 (Figure 1). Our amputee subject's stance-averaged vertical force at top speed was 0.46
151 W_b lower than the values measured for male track athletes (13) at the same top speed
152 (1.87 vs. 2.30 [0.13] W_b). However, in contrast to his extreme swing times and relatively
153 long contact lengths, the ground forces he applied were typical (11), falling well within
154 the range of values reported (1.65-2.52 W_b) for a heterogeneous group of active subjects
155 with intact limbs (top speed range: 6.8-11.1 m/s) that included two accomplished male
156 sprinters.

157

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

166 Because top speeds can be used to predict 200 and 400 m run times to within
167 3.5% or less (3, 12) for both intact-limb runners (3, 12) and this amputee subject (13), we
168 can also quantify the performance advantage provided by artificial vs. intact limbs in
169 specific track events. The reduction of our amputee subject's top speed from 10.8 to 8.3
170 m/s, in conjunction with his measured velocity at VO_{2max} at the time of his laboratory
171 testing (5.0 m/s), increases his running-start 200 m time by nearly 6 s (from 21.6 to 27.3
172 s), and his running-start 400 m time by nearly 12 s (from 49.8 to 61.7 s).

173

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

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

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230 **Figure Captions**

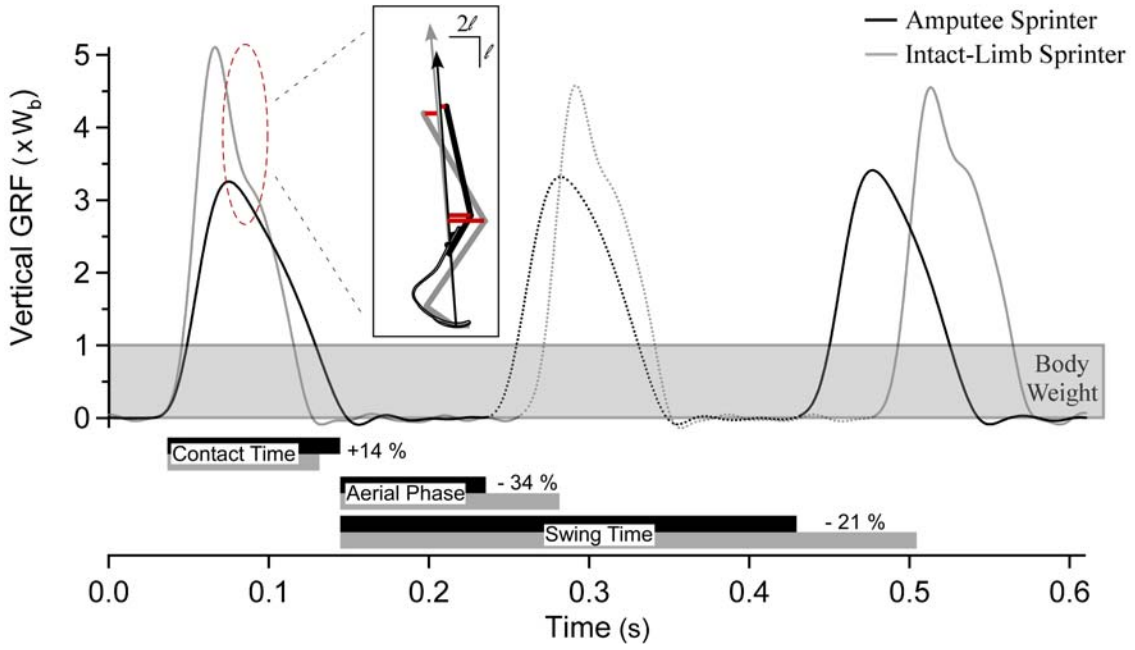
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232 Fig. 1. Vertical ground reaction forces, normalized to body weight vs. time for our
233 amputee sprinter (black) and an intact-limb sprinter (gray) at a treadmill speed of 10.5
234 m/s; shaded region indicates an average force of 1 body weight.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

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269 **Counterpoint:**

270

271 **Artificial legs do not make artificially fast running speeds possible**

272

273

274 **Rodger Kram¹, Alena M. Grabowski², Craig P. McGowan³, Mary Beth Brown⁴ and**

275 **Hugh M. Herr²**

276

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285 “Extraordinary claims require extraordinary evidence” Carl Sagan

286

287 There is insufficient evidence to conclude that modern running specific prostheses (RSP)
288 provide physiological or biomechanical advantages over biological legs. A grand total of
289 $n=7$ metabolic running economy values for amputees using RSP have been published
290 (1,13). Even worse, ground reaction force (GRF) and leg swing time data at sprint speeds
291 exist for only one amputee, Oscar Pistorius (2,13). Until recently it would have been
292 preposterous to consider prosthetic limbs to be advantageous, thus, the burden of proof is
293 on those who claim that RSP are advantageous. Here, we conservatively presume neither
294 advantage nor disadvantage as we weigh and discuss recently published scientific data.
295 Further, we propose a series of experiments that are needed to resolve the topic of this
296 debate.

297

298 RSP do not provide a distinct advantage or disadvantage in terms of the rates of oxygen
299 consumption at sub-maximal running speeds (running economy, RE). Brown et al. (1)
300 compared the RE of six transtibial amputee runners (5 unilateral and 1 bilateral) to six
301 age- and fitness-matched non-amputee runners. The mean RE was numerically worse for
302 the amputees using RSP across all speeds (219.5 vs. 202.2 mlO₂/kg/km), but the
303 difference did not reach the criterion of significance ($p < 0.05$). The bilateral transtibial
304 amputee from Brown et al. had a mean RE of 216.5 ml O₂/kg/km. The only other
305 reported RE value for a bilateral amputee is that for Oscar Pistorius, 174.9 mlO₂/kg/km
306 (13). For good recreational runners ($n=16$), Morgan et al. (9) reported a mean [SD] RE
307 value of 190.5 [13.6] mlO₂/kg/km. Thus, the Brown et al. bilateral amputee’s RE was
308 1.92 SD above that mean and Pistorius’ RE was 1.15 SD below that mean. Both athletes
309 use the same type of prostheses. From this scant evidence, it would be foolhardy to
310 conclude that RSP provide a metabolic advantage or disadvantage.

311 Since vertical GRF is the primary determinant of maximal running speed (11,12), GRF
312 data for amputee runners are critical to this debate. Although previous studies have
313 characterized some aspects of the biomechanics of amputee running and sprinting
314 (3,4,6,7,8,15), there are no published GRF data for unilateral amputees at their top
315 running speeds. GRF data for top speed running have been published for only one
316 bilateral amputee, Oscar Pistorius. To claim that prosthetic legs provide a mechanical
317 advantage over biological legs based upon $n=1$ is inherently unscientific and we are
318 surprised that any scientists would make such a claim.

319

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

329

330 Two factors may be responsible for the GRF deficit that Pistorius exhibits: 1. his passive,

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

340
341 Although Weyand et al. (12) stated “more rapid repositioning of limbs contributes little to
342 the faster top speeds of swifter runners”, Weyand and Bundle (14) argue that Pistorius is
343 able to run fast because his lightweight prostheses allow him to rapidly reposition his legs
344 during the swing phase. Brief leg swing times increase the fraction of a stride that a leg
345 is in contact with the ground and thus reduce the vertical impulse requirement for the
346 contact phase. But, the notion that lightweight prostheses are the only reason for
347 Pistorius’ rapid swing times ignores that he has had many years to train and adapt his
348 neuromuscular system to using prostheses. Weyand and Bundle (14) argue that
349 lightweight prostheses allow Pistorius to run faster than he should for his innate
350 strength/ability to exert vertical GRFs. An equally plausible hypothesis is that he has
351 adopted rapid leg swing times to compensate for the force limitations imposed by his
352 prostheses.

353
354 Pistorius’ leg swing times are not unreasonably or unnaturally fast. Non-elite runners
355 have mean [SD] minimum leg swing times of 0.373 [0.03] sec (12). Pistorius’ leg swing
356 time of 0.284 sec at 10.8 m/s is nearly 3 SD faster than that mean. However, leg swing
357 times as low as 0.31 sec for Olympic 100m medalists at top speed have been reported
358 (12). If elite sprinters have similar variation in leg swing times, then a leg swing time of
359 0.284 sec is not aberrant. Further, recreational athletes sprinting along small radius (1m)
360 circular paths exhibited mean leg swing times of just 0.234 sec (5). It appears that when
361 faced with stringent force constraints, runners with biological legs choose very short leg
362 swing times. A thorough study of leg swing times for elite Olympic and Paralympic
363 sprinters could provide further perspective.

364
365 Fortunately, there are simple experiments with testable hypotheses that can resolve many
366 of the issues presented here. We propose a comprehensive biomechanical study of high-
367 speed running by elite, unilateral amputee athletes. Studying unilateral amputees would
368 allow direct comparisons between their affected and unaffected legs. First, we
369 hypothesize that unilateral amputee sprinters exert greater vertical GRFs with their
370 unaffected leg than with their affected leg. If that hypothesis is supported by data, it
371 would indicate that RSP impose a force limitation and are thus disadvantageous.
372 Second, we hypothesize that unilateral amputee sprinters run with equally rapid leg swing
373 times for their affected and unaffected legs. If that hypothesis is supported, it would
374 dispel the idea that lightweight prostheses provide a leg swing time advantage. Third, we
375 hypothesize that adding mass to the lightweight RSP of unilateral and bilateral amputees
376 will not increase their leg swing times or decrease their maximum running speeds. If that

377 hypothesis is supported, then the assertion that the low inertia of RSPs provide an
378 unnatural advantage would be discredited. Given that some Paralympic sprinters choose
379 to add mass to their prostheses, we anticipate that added mass will not significantly slow
380 leg swing times. Future experiments should also quantify how RSPs affect accelerations
381 and curve running. Both require greater force and power outputs than straight-ahead
382 steady speed running. We hope that the data needed to test these hypotheses will be
383 forthcoming so that this debate can be elevated from a discussion of what might be to a
384 discussion of what is known.

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REBUTTAL

Point: Artificial limbs do make artificial running speeds possible

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

515

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

527

528 The artificial-limb value is also -1.7 and -2.2 active and elite population SD units,
529 respectively, below the single lowest intact-limb swing time (9) ever published (0.317 s),
530 and 16.6% shorter than the mean of the six former 100-meter, world-record holders
531 (0.339 s) in the elite sample above. The artificial-limb value under consideration is not
532 simply an outlier; it is quite literally off the biological charts.

533

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

539

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

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REBUTTAL

Counterpoint: Artificial limbs do not make artificial running speeds possible

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613 “You cannot be serious!” John McEnroe

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615 Weyand and Bundle’s “calculation” (4) that modern passive prostheses provide a
616 12 second advantage over 400m is absurd and insulting to Paralympic athletes.
617 Nearly any schoolboy athlete can run 400m under 60 seconds. Every year,
618 thousands of athletes run under 50 seconds, yet only one amputee has ever
619 broken 50 seconds. Would Weyand and Bundle predict that the world record
620 holder, Michael Johnson, would run 31 seconds if he had both legs amputated?

621

622 We reject Weyand and Bundle’s (4) assertion that lightweight prostheses
623 facilitate unnaturally rapid leg swing times that reduce the force required for
624 amputee runners to run as fast as non-amputees. Rather than being beneficial,
625 a recent study of six, unilateral, amputee sprinters demonstrated that prosthetic
626 legs impair force production (2). At top speed, the stance average vertical force
627 exerted by the affected leg (AL) was 9% less than for the unaffected leg (UL) (P
628 < 0.0001). Recall that Weyand et al. (3) emphasized that vertical force
629 generation is the primary determinant of top speed. Thus, running-specific
630 prostheses likely limit the top speeds of amputee sprinters. Impaired force
631 generation also likely impacts acceleration and curve running performance (1).

632

633 Several lines of evidence (2) show that the leg swing times (t_{sw}) used by amputee
634 sprinters are not unnaturally fast. Video analysis of the 2008 Paralympic Games
635 revealed that the 1st place bilateral amputee’s mean t_{sw} was $0.302 \pm SE 0.003s$ in

636 the 100m and 0.318 ± 0.003 s in the 200m. The 2nd place finisher in the 200m
637 was a unilateral amputee with equally rapid average t_{sw} of 0.304 ± 0.005 s for his
638 UL and 0.323 ± 0.004 s for his AL. Thus, the unilateral amputee runner swings his
639 natural leg as fast or faster than either his or the bilateral amputee's lightweight
640 artificial legs. Video analysis of the 2008 Olympic 100m revealed mean t_{sw} of
641 0.328, 0.305 and 0.274s for the first three finishers. Thus, the t_{sw} of Paralympic
642 sprint medalists were quite similar to those of their Olympic cohorts.

643

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

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