ARTICLE

Athletes With Versus Without Leg Amputations: Different Biomechanics, Similar Running Economy

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BECK, O.N. and A.M. GRABOWSKI. Athletes with versus without leg amputations: different biomechanics, similar running economy. *Exerc. Sport Sci. Rev.*, Vol. 47, No. 1, pp. 15–21, 2019. *Athletes with transtibial amputations use carbon-fiber prostheses to run. Compared with biological legs, these devices differ in structure and function, and consequently yield affected leg running biomechanics that are theoretically more economical than those of nonamputees. However, experimental data indicate that athletes with unilateral and bilateral transtibial amputations exhibit running economy values that are well within the range of nonamputee values.* **Key Words:** amputee, prosthesis, metabolic, cost of transport

Key Points

- Athletes with unilateral and bilateral transtibial amputations use passive-elastic carbon-fiber running-specific prostheses to run.
- Running-specific prostheses do not fully replicate the function of biological legs and thereby contribute to different running biomechanics for athletes with versus without transtibial amputations.
- Despite differences in leg architecture and biomechanics, the running economy values of athletes with unilateral and bilateral transtibial amputations are not different than those of nonamputees.

INTRODUCTION

Olympic athletes who compete in distance-running events (≥5000 m) typically possess a large aerobic capacity (1,2) and exceptional running economy (1,2). Aerobic capacity ($\dot{V}O_{2max}$, $\dot{E}_{aeromax}$) indicates the maximum metabolic rate that an athlete can expend aerobically (3), and running economy is the athlete's submaximal metabolic rate while running at a given steady-state condition (speed, slope, terrain, etc.) (3). An athlete's aerobic capacity and running economy often are used in combination to calculate relative aerobic intensity (*e.g.*, $\%\dot{V}O_{2max}$ $\%\dot{E}_{aeromax}$) during running (3). While considering other factors, an athlete who uses the lowest relative aerobic intensity at a given running speed typically outperforms his or her competitors through his or her ability to run farther at a given speed and faster at matched relative aerobic intensities (1). Thus, increasing aerobic capacity or improving running economy reduces an athlete's relative aerobic intensity to run at a given speed, which in turn improves his or her distance-running performance (1).

Athletes with transtibial amputations use passive-elastic carbon-fiber running-specific prostheses (RSPs) to run and compete with nonamputees in distance-running events (4,5). After an amputation and sufficient recovery, athletes who want to run typically acquire a socket and RSP. First, a prosthetist fabricates a custom socket that is secured to an athlete's residual limb. Then, the prosthetist attaches the RSP to the socket using bolts or pylon attachments, such that the RSP acts in-series to the residual limb. Analogous to running shoes, RSPs are available in different models with different geometries and mechanical properties (4,5). Furthermore, the prosthetist uses manufacturer guidelines, personal experience, and athlete feedback to select a prosthetic stiffness category, RSP-socket alignment, and prosthetic height.

During running, RSPs emulate the spring-like function of biological legs by storing and returning mechanical energy during the first and second half of ground contact, respectively (5–7). The spring-like action of RSPs helps conserve the fundamental spring-like behavior of terrestrial running (8) for athletes with transtibial amputations (9–12). However, RSPs do not fully replicate biological leg function (4,5). For instance, unlike biological legs, RSPs cannot generate mechanical power *de novo* (5), RSP stiffness cannot be adjusted neurally (5), and low-RSP mass yields a smaller moment of inertia compared with biological lower legs (13). Consequently, athletes with transtibial amputations using RSPs adopt running biomechanics (stride kinematics and kinetics) that differ from nonamputees (9,13,14). Often, altered running biomechanics affect economy for both athletes with (6,7) and without (15) transtibial amputations. Hence,

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the dissimilar leg characteristics and running biomechanics of athletes with transtibial amputations using RSPs compared with nonamputees (9,13,14,16,17) may yield inherently different running economy values between cohorts (13,14). In the following sections, we aim to determine whether biomechanical differences explain the literature-wide running economy data of athletes with versus without transtibial amputations.

RSPS

Background and Terms

Unless otherwise stated, we define running economy as gross metabolic cost of transport (CoT) (mL $O_2 \cdot kg^{-1} \cdot km^{-1}$) because it enables us to compare running economy values for athletes tested at different speeds due to CoT's general independence with running speed (15,18,19). We normalize oxygen uptake to athlete mass, which includes biological mass and running gear mass. In addition, prosthetic configuration alters the biomechanics and running economy of athletes with transtibial amputations (7,20). Hence, we limit our analyses to athletes with transtibial amputations using passive-elastic carbon-fiber RSPs without heel components. Moreover, running biomechanics depend on prosthetic model, stiffness, and height (6,7,12), thus we simply assume that all legs with RSPs (affected legs) exhibit identical biomechanics to those of athletes with bilateral transtibial amputations and that all biological legs (unaffected legs) exhibit identical biomechanics to those of nonamputees during running. For the experimental running economy comparisons, if a study reported an athlete's running economy at more than one speed (14,20) or RSP model, stiffness, and height configuration (6,7), we used the best reported value from the corresponding athlete.

BIOMECHANICS COMPARISONS

During running, athlete leg muscles cyclically contract in a coordinated fashion. Muscles generate force and expend metabolic energy during each contraction, irrespective of whether they change length. Muscles expend more metabolic energy when they generate a given force during shortening (concentric contraction) than when they do not change length (isometric contraction) (21–23). When muscles generate force during shortening, they perform positive mechanical work. Classically, scientists related running economy values to the respective athlete's mechanical work to move his or her center of mass (CoM) and limb segments (24–27). However, the associations between 1) muscle mechanical work and external (CoM)/internal (limbs) mechanical work and 2) external/internal mechanical work and CoT during running are related poorly (26,27). Alternatively, running economy changes are well-explained by the magnitude of force that muscles exert on the ground (28,29), as well as the rate of generating this force (30). Altogether, *muscle* mechanical work, muscle force generation, and the rate of muscle force production govern running economy for athletes with and without transtibial amputations.

Athletes expend metabolic energy in direct proportion to the leg extensor force over each running stride (28–30). During running, active leg extensor muscles must generate force and counteract the corresponding external leg joint moment (31). Greater external leg-joint moments require an increased volume of active muscle, involving more adenosine triphosphate (ATP)-utilizing actin and myosin cross-bridge cycles (27,32). Unlike biological legs, RSPs do not contain muscles and thus passively counteract the ground reaction force (GRF)-prosthetic "ankle" joint moment. Furthermore, the muscles surrounding the ankle joint of nonamputees (69.1 ± 9.3 kg; avg ± SD) produce 24 J of net positive mechanical work during ground contact while running 4.8 ± 0.5 $m \cdot s^{-1}$ (avg ± SD) (33); RSPs cannot produce net positive work. Furthermore, RSPs function as viscoelastic springs, indicating that some of their stored elastic energy is dissipated as heat and not converted to gravitational and kinetic energy. As such, RSPs (stiffness, 24.9 $kN \cdot m^{-1}$; hysteresis, 4%) yield about −3 J of net work due to the dissipated mechanical energy during each ground contact during running, assuming a 70-kg body mass and peak vertical GRF that is 2.81 times body weight (34). Thus, to keep similar stride kinematics, the muscles surrounding the affected leg hip or knee joints theoretically need to produce an additional 27 J when using an RSP compared with an unaffected lower limb. For simplicity, and because the muscles surrounding the unaffected leg hip and knee joints yield net positive and negative mechanical energy during running, respectively (33), we predict that the additional muscle volume activated from the muscles surrounding the affected leg's hip joint must produce an additional 27 J per ground contact.

Based on a range of motion ($\Delta\theta$) equal to 0.47 rad (35) and a weighted internal hip joint moment arm ($\bar{r}_{hip}$) of 5.7 cm (31), average hip muscle force (F_{hip}) would increase 1005 N to generate the additional 27 Joules (J):

$$\frac{J}{\Delta\theta} = GRF_{avg} \cdot R_{hip} = F_{hip} \cdot \bar{r}_{hip} \qquad \text{(Eq. 1)}$$

where GRF_{avg} is stance average ground reaction force and R_{hip} is the GRF-hip joint moment arm. Furthermore, we estimated the additional hip joint active muscle volume (V_{hip}) to generate 1005 N using the same methods as (27,30), which incorporates the weighted hip extensor fascicle length ($\bar{l}_{hip}$ = 11.7 cm) (31) divided by a constant muscle stress (*e.g.*, σ = 20 $N \cdot cm^{-2}$) (36).

$$V_{hip} = \frac{F_{hip} \cdot \bar{l}_{hip}}{\sigma} \qquad \text{(Eq. 2)}$$

This calculation ignores compounding biomechanical changes due to running with an RSP rather than a biological leg (*e.g.*, lower GRF magnitude, altered leg joint mechanical work and effective mechanical advantage, etc.). Nonetheless, we estimate that athletes with transtibial amputations need to activate an additional affected leg hip joint muscle volume of 588 cm^3 compared with nonamputees during running. Average active ankle and total leg muscle volume at 4.44 $m \cdot s^{-1}$ is 982 and 2808 cm^3 for nonamputees, respectively (37). Thus, replacing the active ankle joint muscle volume (982 cm^3) with the additional hip joint muscle volume (588 cm^3) predicts that athletes with unilateral and bilateral transtibial amputations use 7.0% and 14.0% less total leg active muscle volume during each running ground contact compared with nonamputees, respectively.

Some of the assumptions we made to estimate active muscle volume differences between athletes with and without transtibial amputations are incomplete. For example, athletes with bilateral transtibial amputations yield 12.4% lower stance average vertical GRFs than nonamputees while running at 4.5 m·s^{-1} (12,37). Therefore, the affected leg's metabolic cost of supporting body weight over each ground contact compared with the unaffected leg's cost *à la* the updated "cost of force generating hypothesis" (30,37) would estimate an even better running economy. Accordingly, if stance average muscle volume is reduced by 12.4% for an affected leg (assuming a constant effective mechanical advantage), this predicts 24.7% lower affected leg active muscle volume compared with that of the biological leg at 4.5 m·s^{-1}. Based on these estimates, athletes with unilateral and bilateral transtibial amputations potentially require 12.8% and 24.7% less active muscle volume than nonamputees to generate force during ground contact at 4.5 m·s^{-1}, respectively. While considering other variables, a 12.8% and 24.7% reduction in active muscle volume yields 12.8% and 24.7% better running economy values using the updated cost of generating force hypothesis (equation 3), respectively, which explains 98% of the increase in metabolic rate in nonamputees from 2.2 to 5.0 m·s^{-1} (37).

$$\dot{E}_{metab} = k\frac{V_m}{t_c} \qquad \text{(Eq. 3)}$$

$\dot{E}_{metab}$ is metabolic rate, k is a constant, V_m is the total leg active muscle volume per ground contact, and t_c is ground contact time.

During running, there is a finite time that muscles have to generate force on the ground over each step. Decreasing this time incurs higher metabolic rates due to the body's recruitment of faster, less economical muscle fibers (32). Accordingly, some studies use the inverse of ground contact time as the rate of generating force and use it to predict metabolic rates (27,30,37) (equation 3). Across distance-running speeds (2.2 to 5.0 m·s^{-1}), ground contact time is generally similar for athletes with and without transtibial amputations (Fig. 1) (6,7,12,34,37). For instance, based on the respective regression equations, ground contact time at 3.84 m·s^{-1} is 0.221 s for athletes with bilateral transtibial amputations (RSP stiffness, 24.9 kN·m^{-1}) (12) and for nonamputees (37). Although ground contact time is generally similar for athletes with and without transtibial amputations across distance running speeds, ground contact time is numerically 6.5% longer for affected legs versus unaffected legs at 4.5 m·s^{-1} (RSP stiffness of 24.9 kN·m^{-1}) (0.213 vs 0.200 s) (12,37). Thus, solely based on contact time differences, equation 3 predicts that athletes with unilateral and bilateral transtibial amputations would be 3.1% and 6.1% more economical runners than nonamputees at 4.5 m·s^{-1}, respectively.

There are other biomechanical differences that may affect running economy in athletes with and without transtibial amputations. Although muscle dynamics during ground contact dominate metabolic cost, there is a cost of swinging the legs during running (15). As such, adding 100 g to a nonamputee's foot and shank increases the rate of oxygen uptake by ~1.0% and ~0.7%, respectively (40). Because the distal RSP is ~1100 g less than a biological foot and the proximal RSP, socket, and affected leg residual shank are ~700 g less than a biological shank (13), the cost of affected leg swing is likely lower than biological leg swing. Specifically, if subtracting

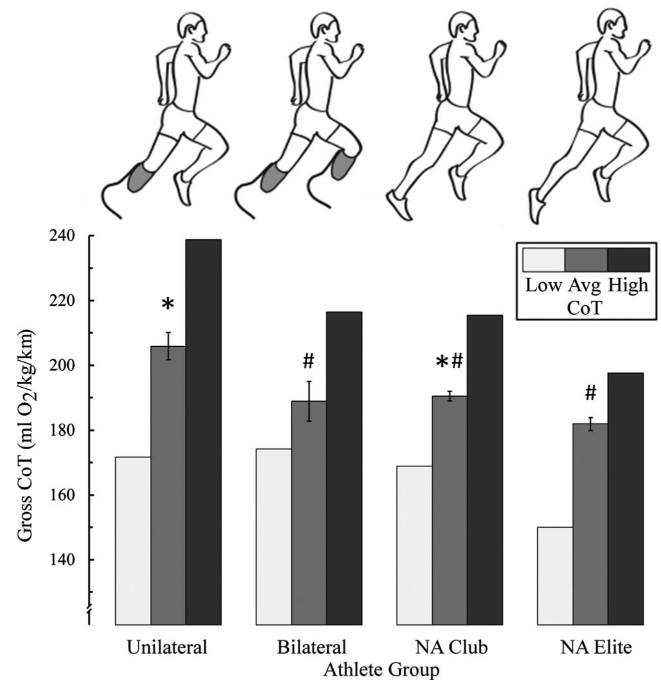

Figure 1. The lowest (light gray), average (medium gray), and highest (dark gray) gross cost of transport (CoT) reported from athletes with unilateral and bilateral transtibial amputations using running-specific prostheses (RSPs) and from nonamputee (NA) club and elite runners. Error bars indicate SE. For athletes with unilateral transtibial amputations, the lowest CoT value is from Beck *et al.* (6), the average CoT value is from Beck *et al.* (6) and Brown *et al.* (20), and the highest CoT value is from Brown *et al.* (20). For athletes with bilateral transtibial amputations, the lowest CoT value is from Beck *et al.* (7), the average CoT value is from Beck *et al.* (7) and Brown *et al.* (20) (recorded by Weyand *et al.* (14)), and the highest CoT value is from Brown *et al.* (20). For NA club runners (36 to 46 min 10-km runners), all CoT values are from Morgan *et al.* (38). For NA elite male runners, the lowest CoT value is from Lucia *et al.* (39), and the average and highest CoT values are from Morgan *et al.* (38). *Indicates a statistical difference compared with average CoT from elite NAs. #Indicates a statistical difference compared with average CoT from athletes with unilateral transtibial amputations.

100 g from the foot improves running economy by ~1.0% and subtracting 100 g from the shank improves running economy by ~0.7%, the metabolic cost of swinging affected versus unaffected legs theoretically reduces metabolic cost by 15.9% (1100 g · 1% + 700 g · 0.7%). However, the metabolic cost of leg swing comprises only 7% of the whole-body net metabolic cost of running in nonamputees, suggesting that reducing leg mass incurs a relatively smaller effect for athletes with bilateral transtibial amputations. If the mass of the leg scales in direct proportion with the metabolic cost of leg swing (7%), we estimate that affected leg swing comprises 2.8% of the net metabolic cost of running in athletes with bilateral transtibial amputations. This is because the affected leg's RSP plus shank mass is ~40% of the unaffected leg's foot and shank mass.

In the aforementioned analyses, we estimated how a few key biomechanical differences with physiological relevance for nonamputees can be used to predict the running economy of athletes with transtibial amputations. Compared with nonamputees, athletes with unilateral and bilateral transtibial amputations "should" have reduced metabolic costs of generating force and swinging legs across distance-running speeds. Further, the cost of the rate of generating force during stance is similar between cohorts, albeit numerically lower for affected versus unaffected legs at 4.5 m·s^{-1}.

EXPERIMENTAL RUNNING ECONOMY COMPARISONS

To assess whether running economy is affected by amputation(s), we compiled and compared literature values of CoT for athletes with unilateral, bilateral, and without transtibial amputations, as well as the most and least economical values from each cohort.

Running Economy Values for Athletes With Transtibial Amputations

To date, published steady-state running economy data of 15 athletes with unilateral transtibial amputations exist (6,20,41) (Table). Collectively, the average ± SD CoT for athletes with unilateral transtibial amputations is 205.9 ± 16.3 mL O_2·kg^{-1}·km^{-1} (6,20,41) and the CoT range is 171.8 to 238.8 mL O_2·kg^{-1}·km^{-1} (Fig. 1) (6,20,41). Because of delayed oxygen uptake kinetics (42), we excluded running economy data from athletes with unilateral transtibial amputations measured within the first 2 min of their running trials (43). Steady-state running economy data from seven athletes with bilateral transtibial amputations exist in the literature (7,14,20,41). The average ± SD CoT for athletes with bilateral transtibial amputations is 188.9 ± 16.3 mL O_2·kg^{-1}·km^{-1} (7,14,20,41) and the CoT range is 174.2 to 216.4 mL O_2·kg^{-1}·km^{-1} (Fig. 1) (7,14,20,41).

Athletes With Unilateral Versus Bilateral Transtibial Amputations

Statistically, the average CoT for 15 athletes with unilateral transtibial amputations (7,14,20) is 9.0% higher than the average CoT for seven athletes with bilateral transtibial amputations (205.9 vs 188.9 mL O_2·kg^{-1}·km^{-1}, respectively; *t*-test, $P = 0.034$; Fig. 1) (6,20). Similarly, the least economical athlete with a unilateral transtibial amputation exhibits a CoT that is 10.4% higher than the least economical athlete with bilateral transtibial amputations (238.8 vs 216.4 mL O_2·kg^{-1}·km^{-1}, respectively) (20,41). However, the most economical athlete with a unilateral transtibial amputation exhibited a CoT that is 1.4% lower than the most economical athlete with bilateral transtibial amputations (171.8 vs 174.2 mL O_2·kg^{-1}·km^{-1}, respectively; Fig. 1) (7).

Athletes With Versus Without Transtibial Amputations

The CoT values of athletes with transtibial amputations are not different from numerous nonamputee cohorts. To reveal which nonamputee cohorts elicit CoTs that are not different from athletes with transtibial amputations, we made select CoT comparisons between athletes with and without transtibial amputations. The average CoT from athletes with unilateral transtibial amputations (205.9 ± 16.3 mL O_2·kg^{-1}·km^{-1}) is not different from that of 10 physically active nonamputee nonrunners (202.2 ± 11.5 mL O_2·kg^{-1}·km^{-1}; *t*-test, $P = 0.815$) (38). The average CoT of athletes with bilateral transtibial amputations (188.9 ± 16.3 mL O_2·kg^{-1}·km^{-1}) is not different from that of nonamputee 10-km club runners (190.5 ± 13.6 mL O_2·kg^{-1}·km^{-1}; *t*-test, $P = 0.793$) (38), nonamputee 3-km runners (mean race times, 10.4 ± 0.95 min average ± SD; 189.5 mL O_2·kg^{-1}·km^{-1}) (44), and nonamputee collegiate and competitive runners (race times, <35 min 10 km; 187.5 ± 9.7 mL O_2·kg^{-1}·km^{-1}; *t*-test, $P = 0.753$; Fig. 1) (38). Furthermore, athletes with unilateral transtibial amputations exhibit 13.1% higher CoTs than elite nonamputee distance runners (181.9 ± 9.1 mL O_2·kg^{-1}·km^{-1}; *t*-test, $P < 0.001$), whereas athletes with bilateral transtibial amputations exhibit CoT values that are not different from the same cohort of elite nonamputee distance runners (*t*-test, $P = 0.158$) (Fig. 1) (38).

To further assess whether athletes with transtibial amputations have running economy values that fall within the range of economy values for nonamputees, we compared the most and least economical CoTs from athletes with transtibial amputations with nonamputee values. The most economical athlete with a unilateral transtibial amputation (6) has a CoT that is 14.5% higher than that of the most economical nonamputee runner (171.8 vs 150.0 mL O_2·kg^{-1}·km^{-1}, respectively; Fig. 1) (39). Moreover, the least economical athlete with a unilateral transtibial amputations exhibits a 4.1% lower CoT than the least economical nonamputee college-aged runner reported by Beck *et al.* (238.8 vs 249.0 mL O_2·kg^{-1}·km^{-1}) (45), indicating that the most and least economical athletes with a transtibial amputation are well-within the CoT range of nonamputees (Fig. 2).

NORMALIZING RUNNING ECONOMY TO BIOLOGICAL MASS

Normalizing CoT to only biological mass, rather than including running gear (clothing, shoe, prosthesis/socket mass), yields relatively higher CoTs for athletes with transtibial amputations compared with nonamputees; particularly for athletes with bilateral transtibial amputations. For instance, the mass of a competition socket plus RSP is ~1.5 kg (7,13,14), whereas the mass of a marathon running shoe is only ~0.23 kg (44). By normalizing rates of oxygen uptake to biological mass (minus 1.5 kg per amputated leg), average CoT increases 2.1% (205.9 to 210.3 mL O_2·kg^{-1}·km^{-1}) and 4.2% (188.9 to 196.9 mL O_2·kg^{-1}·km^{-1}) for athletes with unilateral and bilateral transtibial amputations, respectively. When using CoT and biological mass values indicative of competitive male nonamputee runners (CoT, 190 mL O_2·kg^{-1}·km^{-1}; biological mass plus running gear mass, 70 kg), removing running shoe mass increases CoT by a mere

TABLE. The athletes with unilateral and bilateral transtibial amputations with reported CoT values

Amputation Level	Reference	CoT, (mL O_2·kg^{-1}·km^{-1})	Running Speed (m·s^{-1})	Sample Size (n)
Unilateral	Brown *et al.*, 2009 (20)	218.9 ± 15.5	2.23–3.12	5
Unilateral	Beck *et al.*, 2017b (6)	199.4 ± 12.9	2.5 and 3.0	10
Bilateral	Weyand *et al.*, 2009 (14)	174.2	2.5–4.5	1
Bilateral	Brown *et al.*, 2009 (20)	216.5	2.23	1
Bilateral	Beck *et al.*, 2017a (7)	186.2 ± 12.3	2.5 and 3.0	5

Gross cost of transport (CoT) from athletes with transtibial amputations using running-specific prostheses (RSPs). Average ± SD when applicable.

0.03% (44). Still, normalizing CoT to only biological mass results in economy values for athletes with unilateral and bilateral transtibial amputations that are still within the range for nonamputees (38,39,45).

PREDICTED VERSUS MEASURED RUNNING ECONOMY

Predicting running economy values for athletes with versus without transtibial amputations using biomechanical measures does not concur with experimental oxygen uptake data. By adding up biomechanical differences between cohorts (stance phase active muscle volume and the cost of leg swing), we predicted that athletes with unilateral and bilateral transtibial amputations are 16.9% and 32.1% more economical runners than nonamputees 4.5 m·s$_{-1}$, respectively. However, the experimental running economy data suggest that athletes with unilateral, bilateral, and without transtibial amputations do not yield dramatically different running economy values. To illustrate this point, if the least economical athlete with bilateral transtibial amputations somehow became a nonamputee with biological legs, he would theoretically be 32.1% less economical, yielding a CoT of 285.9 mL O_2·kg^{-1}·km^{-1} (Fig. 2), which is over three SDs greater than the average CoT from college-aged runners at 2.46 m·s^{-1} (38). In addition, a 285.9 mL O_2·kg^{-1}·km^{-1} CoT would require a submaximal $\dot{V}O_2$ of 60.0 mL O_2·kg^{-1}·min^{-1} to run a mere 3.5 m·s^{-1}. Furthermore, if the most economical athlete with unilateral transtibial amputations became a bilateral amputee, she would theoretically become 11.9% more economical and elicit a CoT that is 8.3% lower than the female marathon world record holder (165 mL O_2·kg^{-1}·km^{-1}) (46) and only 0.9% higher than the most economical male runner ever reported (150 mL O_2·kg^{-1}·km^{-1}) (39). Alternatively, if the most economical nonamputee became 32.1% more economical (*e.g.*, equivalent to a predicted athlete with bilateral transtibial amputations), he would theoretically exhibit a CoT of 101.8 mL O_2·kg^{-1}·km^{-1} (Fig. 2). This CoT would require only 21.4 mL O_2·kg^{-1}·km^{-1} to run 3.5 m·s^{-1}. These examples are not realistic and strongly emphasize that there is a disconnect between predicting the running economy of athletes with transtibial amputations using the biomechanical factors that govern economy for nonamputees versus the experimentally measured economy values (Fig. 2).

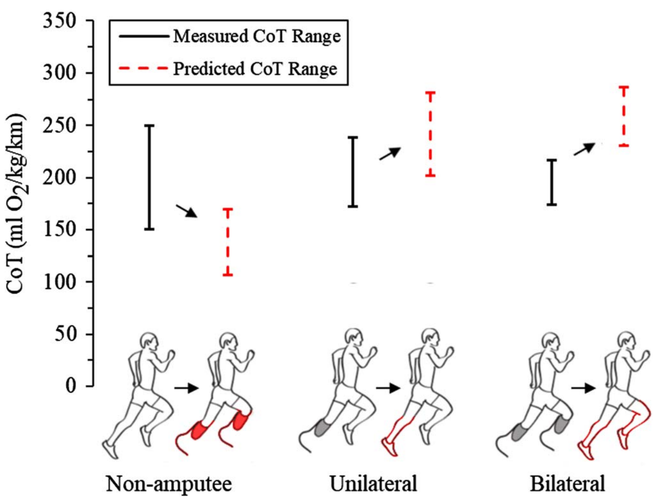

Figure 2. The measured (black solid line) and predicted (red dashed line) range of cost of transport (CoT) values for nonamputees and athletes with unilateral and bilateral transtibial amputations during running. The theoretical predicted CoT range is presented for (left to right) nonamputees running with biomechanics that resemble athletes with bilateral transtibial amputations and for athletes with unilateral and bilateral transtibial amputations using nonamputee biomechanics.

To reiterate, distance-running performance is influenced by aerobic capacity, running economy, and other physiological variables (47). However, regardless of whether athletes with transtibial amputations are more or less economical than nonamputees, their distance-running performance may or may not directly reflect economy differences. For example, a previous study found that an athlete with bilateral transtibial amputations had a 17% and 7.6% lower CoT and $\dot{V}O_{2max}$ compared with select nonamputees, respectively. Yet, these physiological differences yielded nearly identical running velocities at $\dot{V}O_{2max}$, which is an excellent predictor of distance-running performance. Unfortunately, the distance-running potential of athletes with transtibial amputations may not be realized until the Paralympics and World Para Athletics Championships include distance-running track events for these athletes.

LIMITATIONS AND FUTURE DIRECTION

There are potential limitations regarding our comparisons. To start, we made assumptions based on data from nonamputees to predict how different biomechanical variables affect running economy for athletes with transtibial amputations. Furthermore, previous research has demonstrated that running biomechanics synergistically, not independently, affect running economy (15). Thus, simply adding up the influence of individual biomechanical parameters likely overestimates the predicted running economy differences. A battery of future studies are warranted to quantify the biomechanical measures that pertain to running economy for athletes with transtibial amputations. Next, one or more athletes with transtibial amputations may have participated in multiple studies. Accordingly, we may have included the same athlete's running biomechanics and economy data more than once when determining cohort averages. In addition, comparing CoT data from athletes tested in different labs may be influenced by the study's running speed (48,49), altitude (50), metabolic cart breathing valves (51), and treadmill deck compliance (52). Furthermore, the CoT values of many athletes with and without transtibial amputations can be reduced further by using RSPs (6,7) and running shoes (53) that elicit more economical running than their current equipment, respectively. Moreover, numerous studies report nonamputee running economy data, making it possible to find nonamputee running economy data that are similar or different to those of athletes with transtibial amputations.

Even with carefully measured active muscle volume and contact time measures, it is apparent that the cost of generating force hypothesis does not accurately predict metabolic rates for athletes with transtibial amputations. Other biomechanical measures likely complicate the hypothesis' predictions across athletes with and without transtibial amputations (with or without leg swing costs). For example, athletes with bilateral transtibial amputations exhibit faster step frequencies than nonamputees, incurring a greater cost of muscle activation-deactivation (54). The interface between the residual limb and socket may be a source of mechanical energy dissipation, and pistoning between the limb-socket may increase the limb's activation during running.

Furthermore, physiological measures such as hemodynamics and thermoregulation may be impaired in athletes with leg amputations, thereby incurring greater metabolic costs. In all, future work is needed to elucidate how biomechanical and physiological parameters affect running economy comparisons between athletes with and without transtibial amputations.

CONCLUSION AND NOVEL HYPOTHESIS

Despite different biomechanics, current running economy data from athletes with unilateral and bilateral transtibial amputations are well-within the range of nonamputee data. Therefore, we hypothesize that predicting running economy values for athletes with transtibial amputations while ignoring other biomechanical parameters associated with using a socket/RSP or physiological factors associated with amputation does not reflect actual running economy values (Fig. 2).

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