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ORIGINAL ARTICLE

Added lower limb mass does not affect biomechanical asymmetry but increases metabolic power in runners with a unilateral transtibial amputation

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Abstract

Purpose we determined the metabolic and biomechanical effects of adding mass to the running-specific prosthesis (RSP) and biological foot of individuals with a unilateral transtibial amputation (TTA) during running.

Methods 10 individuals (8 males, 2 females) with a TTA ran on a force-measuring treadmill at 2.5 m/s with 100 g and 300 g added to their RSP alone or to their RSP and biological foot while we measured their metabolic rates and calculated peak vertical ground reaction force (vGRF), stance-average vGRF, and step time symmetry indices.

Results for every 100 g added to the RSP alone, metabolic power increased by 0.86% ($p = 0.007$) and for every 100 g added to the RSP and biological foot, metabolic power increased by 1.74% ($p < 0.001$) during running. Adding mass had no effect on peak vGRF ($p = 0.102$), stance-average vGRF ($p = 0.675$), or step time ($p = 0.413$) symmetry indices. We also found that the swing time of the affected leg was shorter than the unaffected leg across conditions ($p < 0.007$).

Conclusions adding mass to the lower limbs of runners with a TTA increased metabolic power by more than what has been reported for those without an amputation. We found no effect of added mass on biomechanical asymmetry, but the affected leg had consistently shorter swing times than the unaffected leg. This suggests that individuals with a TTA maintain asymmetries despite changes in RSP mass and that lightweight prostheses could improve performance by minimizing metabolic power without affecting asymmetry.

Keywords Amputee · Symmetry · Energetics · Economy · Prosthesis

Abbreviations

RSP	Running-specific prosthesis
SI	Symmetry index
TTA	Transtibial amputation
vGRF	Vertical ground reaction force

Introduction

Metabolic power and oxygen consumption increases 1% for every 100 g added to each foot/ankle of runners without amputations across speeds ranging from 3.35 to 4.88 m/s (Frederick et al. 1984; Franz et al. 2012; Hoogkamer et al. 2016; Divert et al. 2008; Fuller et al. 2015; Martin 1985; Jones et al. 1984; Claremont and Hall 1988; Myers and Steudel 1985) and increased metabolic power worsens 3000 m running performance (Hoogkamer et al. 2016). While the directional changes between metabolic power and distance running performance are likely the same for individuals with and without a transtibial amputation (TTA), the effects of added lower limb mass on metabolic power for individuals with a TTA is unknown.

Most individuals with a TTA run using a running-specific prosthesis (RSP), which is a passive-elastic carbon fiber device that lacks an ankle joint and is attached to a carbon fiber socket that surrounds the residual limb. The effect of increased lower limb mass on metabolic power has

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been investigated in runners without a TTA (Modica and Kram 2005; Moed and Kram 2005), but the use of an RSP in individuals with a TTA likely influences the effect of lower limb mass on metabolic power. Because an RSP has approximately half the mass of a biological foot and shank (Brüggemann et al. 2008; De Leva 1996), adding mass to the RSP and biological foot of an individual with a TTA would result in a relatively larger increase in the mass of their affected leg compared to their unaffected leg. Thus, adding mass to the RSP may increase metabolic power by a greater amount in individuals with a TTA compared to values reported in individuals without a TTA.

The structural and functional differences between the biological foot and ankle and RSP of an individual with a TTA result in asymmetric running biomechanics (Beck and Grabowski 2017; Baum et al. 2016; Arellano et al. 2015; McGowan et al. 2012). For example, previous studies found that when individuals with unilateral TTAs used a recommended RSP configuration, their affected leg generated 9% lower stance-average vertical ground reaction forces compared to their unaffected leg across a wide range of running speeds (3m/s—top speed) (Grabowski et al. 2009; Baum et al. 2016). In individuals with and without a TTA, asymmetric running biomechanics have been identified as risk factors for injury (Lloyd et al. 2010; Daly et al. 2016) and increase metabolic cost (Beck et al. 2017). However, adding mass to the RSP of individuals with a TTA may not affect the biomechanics of the affected leg. For example, Grabowski et al. (2009) found that adding 100 and 300 g to the RSP of sprinters with a TTA had no effect on leg swing time, stance-average vGRF, or maximum speed (Grabowski et al. 2009).

When a prosthetist prescribes an RSP to an individual with a TTA, they typically adjust prosthesis height, stiffness, and alignment to reduce kinematic asymmetries such as step frequency between legs (Innovations 2014). However, prosthetists are not often equipped to detect and minimize asymmetries in variables such as peak or stance-average vertical ground reaction force (vGRF), which have been associated with reductions in metabolic cost during running (Beck et al. 2017). Decreases in peak and stance-average vGRF asymmetry have been achieved by changing RSP model and height (Beck et al. 2017), but adding relatively small ($\leq$ 300 g) amounts of mass to the RSP could increase the affected leg peak and stance-average vGRF (Clark et al. 2017), decrease asymmetry, and potentially lower metabolic power during running. Determining how RSP mass affects metabolic cost during running may therefore inform RSP design and rehabilitation strategies seeking to reduce running injury prevalence and improve running performance in individuals with a TTA.

We investigated the metabolic and biomechanical effects of adding mass to the RSP alone or to the RSP and biological foot of individuals with a TTA during running. We hypothesized that adding mass to the RSP alone would decrease peak vGRF, stance-average vGRF, and step time asymmetry. Decreased biomechanical asymmetry in individuals with a TTA could potentially decrease metabolic cost (Beck et al. 2017), but adding mass to the RSP alone may increase metabolic power due to the additional metabolic energy required to support the increased body weight and to swing a heavier leg. Thus, we hypothesized that adding mass to the RSP alone would have no effect on metabolic power due to the offsetting effects of symmetry and biomechanical changes that increase metabolic power when running with added mass. We also hypothesized that mass added to the RSP and biological foot would have no effect on peak vGRF, stance-average vGRF, or step time asymmetry, and would increase metabolic power during running.

Methods

Participants

Ten individuals (8 males, 2 females; mean ± SD: mass 70.3 ± 8.3 kg, height 1.76 ± 0.09 m, age 38 ± 5 years) with a TTA participated. All participants had at least 1 year of experience using an RSP and reported running at least 3 days per week over the 6 months prior to data collection. The protocol was approved by the University of Colorado Boulder Institutional Review Board and all participants provided informed consent prior to participation.

Experimental protocol

Each participant ran on a force-measuring treadmill (1000 Hz; Treadmetrix, Park City, UT, USA) while we measured their rates of oxygen consumption and carbon dioxide production via indirect calorimetry (ParvoMedics TrueOne 2400, Sandy, UT, USA). Participants were instructed to refrain from eating food or drinking anything but water for the 2 h leading up to data collection. Following a 5-min warm-up on the treadmill, participants ran at 2.5 m/s for 5 min under 5 conditions in a random order: no added mass, 100 g added to the RSP alone, 300 g added to the RSP alone, 100 g added to the RSP and biological foot (200 g total), and 300 g added to the RSP and biological foot (600 g total). Participants were given at least 5 min rest between conditions. During each trial we monitored respiratory exchange ratios and ensured that participants maintained primarily aerobic metabolism, indicated by a respiratory exchange ratio < 1.0. We added 100 g and 300 g to allow for comparison with prior work (Grabowski et al. 2009; Franz et al. 2012; Hoogkamer et al. 2016). We adhered the center of

100 g (10 cm × 5 cm × 2 cm) and 300 g (10 cm × 10 cm × 3 cm) 10 cm from the distal end of the RSP or shoe (Fig. 1).

Analysis

We averaged rates of oxygen consumption and carbon dioxide production over the last 2 min of each trial, calculated gross metabolic power (Brockway 1987), and normalized metabolic power to each participant"s body mass including their RSP and running clothes, but excluding the 100 g or 300 g added mass. At most, the added mass constituted ~1% of a runner's body mass, and prior studies have not included this in the normalization of metabolic power (Hoogkamer et al. 2016; Myers and Steudel 1985; Franz et al. 2012). We measured ground reaction forces for 30 s during the final minute of each condition. We used a custom Matlab script (Mathworks, Natick, MA, USA) to filter vGRF data using a zero-lag 4th-order low-pass Butterworth filter with a 30 Hz cut-off and used ten steps from each leg for analyses (Alcantara 2019). Step time was calculated as the time between a limb's initial contact with the ground and the initial contact of the contralateral limb. We defined stance phase as the period when the runner's vGRF exceeded a 20 N threshold. Stance-average vGRF was normalized to body weight and calculated as the mean vGRF during ground contact for each of the respective leg's ten steps. We used the absolute value of the symmetry index (SI) to determine peak vGRF, stance-average vGRF, and step time asymmetry between the affected and unaffected leg (Herzog et al. 1989). Symmetry Index is represented as a percentage (Eq. 1) where perfect symmetry between the affected and unaffected leg is 0%:

Fig. 1 The center of the added mass was adhered 10 cm from the distal end of the shoe on the unaffected leg and of the RSP on the affected leg

$$SI = \left| \frac{\text{Unaffected} - \text{Affected}}{0.5(\text{Unaffected} + \text{Affected})} \right| \times 100 \tag{1}$$

We constructed linear mixed-effects models ($\alpha = 0.05$) to determine the effect of added mass on gross metabolic power, peak vGRF SI, stance-average vGRF SI, and step time SI during running. In each model, condition was considered a fixed effect and participant was considered a random effect. All models were verified for normality of residuals and homogeneity of variance using the Shapiro–Wilk test ($\alpha = 0.05$). Non-statistically significant model coefficients were removed from the model on the basis that the coefficient was not significantly different than 0. Unstandardized model coefficients (B) are reported alongside the p value or within the model equation. Model coefficients represent the change in a dependent variable per unit change in an independent variable. This approach allows us to predict the change in gross metabolic power per 100 g added to the RSP, for example. We analyzed data in R (version 3.5.1) (R Core Team 2019) using custom scripts and packages (Pinheiro et al. 2018; Wickham 2016). We performed an a priori power analysis (Faul et al. 2007) based on prior results (Franz et al. 2012; Grabowski et al. 2009) to determine the appropriate number of participants to include in this study. Ten participants were needed to achieve a power of 0.9 and determine potential changes in metabolic power and limb symmetry due to mass added to the lower limbs during running.

We also performed a post hoc analysis to determine if adding mass to the lower limb affects leg swing time in individuals with a TTA. We calculated leg swing time as the duration between the end of the stance phase and the start of the subsequent stance phase. We constructed a linear mixed-effects model ($\alpha = 0.05$) and considered condition a fixed effect and participant a random effect.

Results

The mean (± standard error) metabolic power of running at 2.5 m/s with no added mass was 11.97 ± 0.35 W/kg. For every 100 g added to the RSP alone, gross metabolic power increased 0.86 ± 0.25% ($p = 0.007$; Fig. 2). When mass was added to the RSP and biological foot, the effect approximately doubled as gross metabolic power increased by 1.74 ± 0.25% per 100 g added to each limb ($p < 0.001$; Fig. 2).

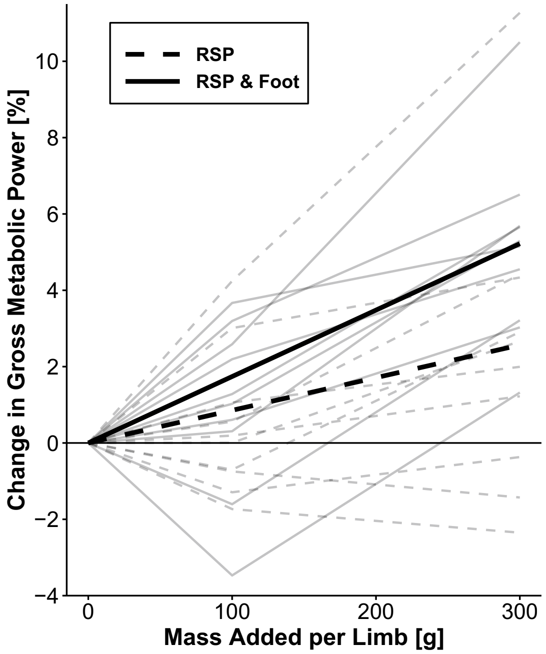

Fig. 2 Percentage change in gross metabolic power for running at 2.5 m/s without added mass and with added mass of 100 and 300 g. Mass added to the RSP alone resulted in a 0.86% increase in metabolic power (W/kg) per 100 g (p = 0.007; Metabolic Power [W/kg] = 11.947 + 0.001 × mass [g]). Mass added to the biological foot and RSP resulted in a 1.74% increase in metabolic power per 100 g added to each foot (p< 0.001; Metabolic Power [W/kg] = 11.924 + 0.002 × mass [g]). Thin lines represent participant-specific data, where the dashed lines indicate mass added to the RSP alone and the solid lines indicate mass added to RSP and biological foot. Thick black lines represent model overall predictions across conditions

When running with no added mass, participants had a mean (± SE) stance-average vGRF SI of 7.39 ± 2.03%, peak vGRF SI of 13.95 ± 2.63%, and step time SI of 5.77 ± 1.58%. There was no significant change in symmetry indices regardless of the amount of mass added (100 or 300 g) or limb(s) mass was added to (RSP alone or RSP and biological foot). There were no differences in stance-average vGRF SI, peak vGRF SI, or step time SI between mass added to the RSP alone or mass added to the RSP and biological foot (p = 0.389, p = 0.442, and p = 0.579, respectively). Further, there were no effects of added mass on stance-average vGRF SI (p = 0.675), peak vGRF SI (p = 0.102), or step time SI (p = 0.413; Table 1).

When running with no additional mass, participants had a mean (± SE) leg swing time of 459 ± 16 ms for the affected leg and 468 ± 18 ms for the unaffected leg. This difference between leg swing times was statistically significant and persisted across added mass conditions. When we added mass to the RSP and biological foot, unaffected leg swing time was 10 ± 3 ms greater than affected leg swing time (p = 0.007), but there was no effect of added mass on leg swing time (p = 0.228). When we added mass to the RSP alone, unaffected leg swing time was 10 ± 3 ms greater than affected leg swing time (p = 0.005) and for every 100 g added to the RSP alone, swing time for both legs increased by 5 ± 1 ms (p = 0.001; Fig. 3).

Discussion

We reject our first and second hypotheses that mass added to the RSP alone would decrease peak vGRF asymmetry, stance-average vGRF, and step time asymmetry and have no effect on metabolic power during running. Although adding mass to the RSP alone reduced the mass discrepancy between the affected and unaffected leg, adding 100–300 g to the RSP had no effect on biomechanical asymmetry but increased metabolic power by 0.86% per 100 g added. This finding highlights a potential area for RSP development, as a lighter RSP may decrease metabolic power while having no effect on biomechanical asymmetry. If a long-distance runner with a TTA was able to decrease their metabolic power using a lighter RSP, they may be able to improve their running performance due to the association between decreased

Table 1 Mean (± SE) symmetry Index (SI) for stance-average vertical ground reaction force (vGRF), peak vGRF, and step time across all conditions

Symmetry Index	Location	Mass added per limb		
		0 g (%)	100 g (%)	300 g (%)
Stance-average vGRF	RSP	7.39 ± 2.03	8.35 ± 1.95	7.59 ± 2.06
	Both		7.54 ± 2.16	7.68 ± 2.01
Peak vGRF	RSP	13.95 ± 2.63	14.01 ± 3.03	12.33 ± 2.82
	Both		13.40 ± 2.79	13.91 ± 2.43
Step time	RSP	5.77 ± 1.58	5.75 ± 1.36	5.23 ± 1.29
	Both		5.66 ± 1.55	5.77 ± 1.48

There were no significant differences ($p > 0.05$) in SI between adding mass to the running specific prosthesis (RSP) alone or adding mass to the RSP and biological foot (both). There were no significant changes in stance-average vGRF, peak vGRF, or step time SI across added mass conditions (B = 0.0005, B = −0.003, B = −0.0009; all $p > 0.05$)

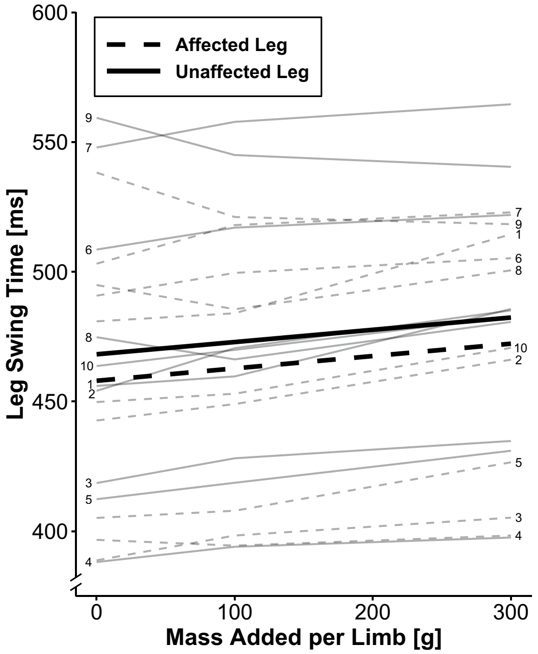

Fig. 3 Swing time of the affected leg and unaffected leg for running at 2.5 m/s without added mass and with added mass of 100 and 300 g to the RSP alone. Across the added mass conditions, unaffected leg swing time was greater than affected leg swing time (p = 0.005), and swing time of both legs increased by 5 ms per 100 g (p = 0.001; Swing time [ms] = 458.01 + 0.0475 × mass [g] + 10.148 × leg [Affected: 0, Unaffected: 1]). Thin lines represent participant-specific data, where the dashed lines indicate the affected leg and the solid lines indicate the unaffected leg. Participant number for unaffected leg swing time is on the left vertical axis and participant number for affected leg swing time is on the right vertical axis. Thick black lines represent model overall predictions across conditions

metabolic power and improved long distance running performance in individuals without a TTA (Hoogkamer et al. 2016). Although adding mass to the RSP alone increased metabolic power in the present study, Beck et al. (2017) found that an optimal combination of RSP model, stiffness, and height increased peak vGRF symmetry and decreased metabolic cost of transport during running at 2.5–3.0 m/s (Beck et al. 2017). Our data suggest that RSP mass does not affect these measures of symmetry, as participants maintained asymmetric peak vGRF, stance-average vGRF, step time, and leg swing time despite running with up to 300 g added to their RSP. While RSP mass had no effect on biomechanical asymmetry, we found that increasing RSP mass increased metabolic power during running.

Adding mass to the RSP and biological foot had no effect on peak vGRF, stance-average vGRF, or step time asymmetry, but increased metabolic power by 1.74% per 100 g added to each limb (RSP and biological foot), which is greater than the reported ~ 1% increase in metabolic power per 100 g added to each foot or ankle in runners without a TTA (Frederick et al. 1984; Franz et al. 2012; Hoogkamer et al. 2016; Fuller et al. 2015; Martin 1985; Jones et al. 1984; Claremont and Hall 1988; Myers and Steudel 1985). We failed to reject our third and fourth hypotheses that mass added to the RSP and biological foot would have no effect on biomechanical asymmetry and that runners with a TTA would experience an increase in metabolic power when mass is added to the RSP and biological foot. Further, our data suggest that individuals with a transtibial amputation may be more metabolically sensitive to mass added to their RSP and biological foot compared to individuals without an amputation, potentially resulting in even slower long distance running performances (Hoogkamer et al. 2016).

The location of mass added to a runner's body has a differential effect on metabolic cost during running. Teunissen et al. (2007) found that when adding mass around the waist, every 10% increase in body mass (~ 6 kg) increased net metabolic power by ~ 13% to run at 3.0 m/s. The greater metabolic cost to run was primarily attributed to the increased force generation required to support body weight (Farley and McMahon 1992; Taylor et al. 1980). We extrapolated these findings to determine the effect of adding 600 g to the waist, which is ~ 1% of the average participant body mass, and found that every 1% increase in body weight around the waist would increase net metabolic power by ~ 1.3%. If a similar mass is added to the lower limbs (300 g on each foot) of runners without a TTA, prior work (Franz et al. 2012; Hoogkamer et al. 2016) suggests that metabolic power would increase by ~ 3%. However, our findings indicate that metabolic power would increase by 5.2% in runners with a TTA due to the 1.74% increase in metabolic power per 100 g on the RSP and biological foot. Further, the mass location affects the time during a stride that the metabolic penalty occurs. For example, when mass is added to the waist, the additional metabolic cost occurs during stance phase due to the additional force that the legs must produce to support the weight of the body during running (Arellano and Kram 2014; Teunissen et al. 2007; Farley and McMahon 1992; Taylor et al. 1980). But when mass is added to the feet, the legs need support the increased body weight and raise the foot with the added mass off the ground, swing it forward, and decelerate it before contacting the ground again (Modica and Kram 2005; Myers and Steudel 1985; Frederick et al. 1984). Thus, added mass to the feet incurs an additional metabolic cost during stance and swing phase.

Adding mass to the feet affects the lower leg's moment of inertia, which influences the metabolic energy required to swing the leg during running (Myers and Steudel 1985; Modica and Kram 2005; Martin 1985). We found that runners with a TTA have a larger increase in metabolic power due to mass added to their RSP and biological foot compared to runners without a TTA (1.74% vs. ~1% increase per 100 g on each foot (Frederick et al. 1984; Franz et al. 2012; Hoogkamer et al. 2016; Divert et al. 2008). Individuals with a TTA have approximately half the mass below the knee on their affected leg compared to a biological leg (Brüggemann et al. 2008; De Leva 1996) and thus 100 g added to the RSP represents a larger relative increase in the lower leg's moment of inertia relative to the knee, and presumably requires more metabolic energy to swing the leg. Using previously published inertial properties for an RSP, socket, and residual limb of a sprinter with TTAs (Brüggemann et al. 2008), we estimate that adding 100 g to the distal end of the RSP would increase the affected leg's moment of inertia by approximately 9% compared to 4% in an individual without a TTA. While the effects of leg moment of inertia on metabolic cost and muscle activation have been examined during walking in individuals with and without a TTA (Royer and Martin 2005; Smith and Martin 2013; Selles et al. 2004), to our knowledge no studies have quantified the relationship between lower leg moment of inertia and metabolic cost during running in individuals with a TTA. We suspect that the greater metabolic costs incurred by individuals with a TTA when mass is added to the RSP are due to these disproportionately larger inertial loads, but this requires further investigation.

We found that adding mass to the RSP alone or to the RSP and biological foot of runners with a TTA had no effect on peak vGRF, stance-average vGRF, and step time asymmetry. It is possible that the mass added to the RSP in the present study was simply not enough to elicit changes in kinetic or kinematic asymmetry. However, we do not suspect that adding larger amounts of mass to the RSP would decrease biomechanical asymmetries enough to offset the increased metabolic power associated with the added mass. Prior work found that a 10% decrease in peak vGRF SI correlated to a 1.9% decrease in net metabolic cost of transport (energy expenditure per unit distance instead of unit time) in runners with a TTA (Beck et al. 2017), but when we added 300 g to the RSP, there was no effect on peak vGRF SI and gross metabolic power increased by ~ 2.6%. Thus, it is likely that any decrease in asymmetry would be outweighed by the metabolic cost of running with an additional mass on the RSP.

Affected and unaffected leg swing time did not change with mass added to the RSP and biological foot, but unaffected leg swing time was consistently longer than affected leg swing time regardless of whether mass was added or not. The swing time of both legs increased as mass was added to the RSP alone. Thus, adding mass to the RSP alone increases affected leg swing time but participants increased unaffected leg swing time and thereby maintained leg swing time asymmetry. Grabowski et al. (2009) found that swing time between the affected and unaffected leg did not differ when adding 100 and 300 g to the RSP compared to no added mass at running speeds of 3 m/s up to maximum speed (Grabowski et al. 2009). However, our findings do not corroborate those of Grabowski et al. (2009) . It is possible that different results between studies are due to differences in statistical power; as Grabowski et al. (2009) state that they may have had limited statistical power due to including six participants in their study (Grabowski et al. 2009).

We chose to add 100 g and 300 g to the RSP and biological foot of our participants to make direct comparisons to prior work (Frederick et al. 1984; Franz et al. 2012; Hoogkamer et al. 2016). A future study investigating how metabolic power is affected by adding a proportional amount of mass to the legs of runners with and without a TTA could further elucidate the effect of added mass on runner's feet by effectively normalizing to lower leg mass. However, small amounts of mass may only be realistically added to the RSP before the socket fit is compromised and becomes unattached from the residual limb during running. We were unable to compare the effect of added mass on metabolic power between male and female runners with a TTA because only 2 females volunteered to participate in the present study. However, we normalized metabolic power to body mass so that we could quantify the effect of added lower limb mass across participants with different body masses. Previous work (Frederick et al. 1984; Franz et al. 2012; Hoogkamer et al. 2016; Divert et al. 2008) has determined how oxygen consumption and metabolic power are affected by adding mass to the shoes of individuals who ran at faster speeds (3.35–4.88 m/s) than the speed we tested (2.5 m/s), which may limit the generalizability of our findings. Additionally, Frederick et al. (1984) found that the effect of added mass on oxygen consumption may decrease with faster speeds (Frederick et al. 1984). While other previous studies have found that metabolic power and oxygen consumption increases ~ 1% for every 100 g added to each foot at speeds from 3.35 to 3.61 m/s (Franz et al. 2012; Hoogkamer et al. 2016; Divert et al. 2008), it is possible that runners with a TTA may experience a reduced effect of added mass at speeds faster than 2.5 m/s. Further studies are required to better understand the effect of added mass on metabolic power across a wide range of running speeds.

Conclusions

Adding 100 and 300 g to the RSP alone increased metabolic power by 0.86% per 100 g and had no effect on stance-average vGRF, peak vGRF, or step time asymmetry. Adding 100 and 300 g to the RSP and biological foot of runners with a TTA increased metabolic power by 1.74% per 100 g on each leg. The swing time of the unaffected leg in runners with a TTA was greater than the swing time of the affected leg across all conditions and adding mass to the RSP alone increased the swing time of both legs proportionally. Adding mass to the RSP and biological foot had no effect on stance-average vGRF, peak vGRF, or step time asymmetry. Thus, adding mass to the RSP alone does not decrease asymmetry and would likely worsen distance running performance due to the associated increase in metabolic power. In contrast, reducing RSP mass may improve distance running performance in individuals with a transtibial amputation by reducing metabolic power while having no effect on biomechanical asymmetry.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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