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Joint work and ground reaction forces during running with daily-use and running-specific prostheses

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ABSTRACT

Some individuals with a transtibial amputation (TTA) may not have access to running-specific prostheses and therefore choose to run using their daily-use prosthesis. Unlike running-specific prostheses, daily-use prostheses are not designed for running and may result in biomechanical differences that influence injury risk. To investigate these potential differences, we assessed the effect of amputation, prosthesis type, and running speed on joint work and ground reaction forces. 13 people with and without a unilateral TTA ran at speeds ranging from 2.5 m/s to 5.0 m/s. People with TTA ran using their own daily-use and running-specific prostheses. Body kinematics and ground reaction forces were collected and used to compute joint work. People with TTA had smaller peak braking, propulsive and medial/lateral ground reaction forces from the amputated leg compared to people without TTA. People wearing running-specific prostheses had smaller peak amputated leg vertical ground reaction forces compared to daily-use prostheses at speeds above 3.5 m/s. Medial/lateral forces were also smaller in running-specific prostheses, which may present balance challenges when running on varied terrain. Running-specific prostheses stored and returned more energy and provided greater propulsion, resulting in more similar positive hip work between legs compared to daily-use prostheses. Increases in positive hip work, but not device work, highlight the importance of the hip in increasing running speed. Running-specific devices may be beneficial for joint health at running-speeds above 3.5 m/s and provide advantages in propulsion and energy return at all speeds compared to daily-use prostheses, helping people with TTA achieve faster running speeds.

1. Introduction

Running is beneficial for physical, emotional, and social health (Kavanagh, 1983; Singh et al., 2007; Taylor et al., 1985) and participation in physical activity is increasing for people with amputations (LimbPower, 2016). Running-specific prostheses (RSPs) are designed for running with a geometry that results in greater deformation compared to a daily-use prosthesis (DUP) in order to increase energy storage and return (McGowan et al., 2012; Nolan, 2008). However, RSPs can be difficult to acquire as they are costly devices that are typically an out-of-pocket expense for individuals. Therefore, people with a transtibial amputation (TTA) who wish to begin running may choose to do so using their DUP, which is a device designed for activities of daily-living rather than highly dynamic activities like running. Given the lack of widespread availability of RSPs, understanding how amputation, device selection, and running speed affect biomechanical outcomes for people with TTA is important to reduce barriers for people with TTA to run.

A unilateral TTA and the associated functional loss of the ankle plantarflexors leads to differences in ground reaction forces (GRFs) (Grabowski et al., 2010; Hobara et al., 2014; Baum et al., 2016) and joint kinetics (Czerniecki et al., 1991; Silverman et al., 2008; Baum et al., 2019; Sanderson and Martin, 1996) between the amputated and intact legs during walking and running. Altered GRFs in people with TTA are contributing factors to limited running performance and greater injury risk. Specifically, smaller peak vertical GRFs on the amputated leg of people with TTA during sprinting limit top running speed (Grabowski et al., 2010) and smaller mediolateral GRFs are associated with challenges in maintaining dynamic balance (Sepp et al., 2019). Differences in joint loading and GRFs between the amputated and intact legs for people with TTA likely contribute to greater risks and rates of joint degeneration, including hip and knee osteoarthritis (Morgenroth et al., 2012; Royer and Wasilewski, 2006; Struyf et al., 2009). Restoring function in the amputated leg to reduce inter-limb differences in GRFs and joint

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kinetics is likely important for improving long-term musculoskeletal health outcomes. While RSPs provide a metabolic benefit over DUPs during running (Mengelkoch et al., 2014), differences between DUPs and RSPs in joint work and GRFs during running for people with TTA remain unclear.

A comprehensive analysis of the effect of running with an amputation while varying device designs and running speed is important to advance prosthetic design and improve function. Evaluating running biomechanics for non-elite runners with TTA is important because access to RSPs is especially limited for this group. Quantifying the influence of prosthesis type on joint work and GRFs is important for understanding long-term joint health and assisting people with TTA in selecting the best prosthesis. Therefore, the purpose of this study was to characterize how (1) the presence of an amputation, (2) the use of an RSP compared to a DUP and (3) running speed affect GRFs and stance phase joint work during running. Given prior evidence of biomechanical asymmetry during running with TTA, we expected to see differences in joint work and GRFs between people with and without TTA and between the amputated and intact legs regardless of the prosthesis type. Further, we expected that these variables would be different between people running using DUPs compared to RSPs because of the differences in energy storage and return characteristics between these types of prosthetic devices. Finally, we expected that joint work and GRFs would increase in magnitude with increases in running speed, regardless of prosthesis type or presence of TTA.

2. Methods

2.1. Participants

Thirteen people with and thirteen people without a unilateral TTA volunteered for this study (Table 1). Participants provided informed consent to the protocol approved by the institutional review board, were free from injury, and did not have an amputation due to vascular disease. People with TTA had at least two months of experience running with their RSP and used their own, clinically prescribed DUP and RSP (Table 1).

2.2. Protocol

Participants ran on an instrumented treadmill (Bertec, Inc., Columbus, OH) at five randomized, steady-state speeds (2.5 m/s, 3.0 m/s, 3.5 m/s, 4.0 m/s, and 5.0 m/s) while GRFs were collected at 2000 Hz. Participants were instrumented with a set of 56 (people without TTA) or 63 (people with TTA) active markers and kinematics were collected with an optoelectric motion capture system at 100 Hz (3DInvestigator, Northern Digital, Inc., Ontario, Canada). The RSP had seven individual markers on the prosthesis to characterize deformation of the carbon-fiber device (4 physical and 3 digitized) (Fig. 1).

2.3. Data analysis

GRFs were low-pass filtered using a dual-pass 4th-order Butterworth filter with a cutoff frequency of 15 Hz, determined using a residual analysis (Winter, 2009). Kinematic data were similarly filtered with a 6 Hz cutoff (Zelik and Honert, 2018; Tominaga et al., 2015). Joint kinetics were computed using an inverse dynamics approach (C-Motion, Inc., Bethesda, MD). For the RSP condition, we built a five-segment model of the prosthesis (Fig. 1). DUP and RSP mass were measured for each participant and inertial properties for RSPs were based on previous measurements (Baum et al., 2013). Center of mass values for the amputated leg were calculated from residual leg volume estimates as a right frustum (Hanavan, 1964). Positive and negative stance phase work were computed by integrating the positive and negative portions of joint power over the stance phase, respectively. Mechanical work at each joint of the RSP was computed and summed to determine the total work performed by the RSP and compared as "ankle joint" work (Rigney et al., 2016) (Fig. 1). Ankle joint work for the amputated side DUP condition was computed using an estimated ankle joint center from markers placed at the same height as the intact leg malleoli (Buckley, 1999). GRFs were normalized to body weight and joint work was normalized to body mass. Five gait cycles from each participant at each speed were used for analysis.

2.4. Statistical analysis

Differences in joint work and peak GRFs were each assessed in R Statistical Computing Software v 1.1.153 using three, three-factor ANOVAs (Pinheiro et al., 2013) with factors of (1) running speed, (2) side, and (3) prosthesis condition (Table 2). The speed factor had five levels (2.5 m/s, 3.0 m/s, 3.5 m/s, 4.0 m/s, and 5.0 m/s), the side factor had two levels (amputated/left vs. intact/right), and the prosthesis condition factor had two levels (Table 2). Tukey's correction for multiple comparisons was used for

Table 1
Participant characteristics.

Sex	Age	Height (m)	Body mass (kg)	**Etiology**	Time since amputation (months)	Running-Specific Prosthesis Type	Daily-Use Prosthesis Type
F	32	1.70	72.4	Congenital	360	Össur Cheetah X-tend	Össur Proflex
F	27	1.71	60.5	Trauma	17	Freedom Innovations Catapult	Össur Proflex
M	41	1.75	70.2	Trauma	197	Össur FlexRun	Ottobock Advantage DP2
M	20	1.76	69.6	Trauma	108	Freedom Innovations Catapult	Freedom Innovations Renegade
F	28	1.64	51.2	Disease	36	Össur Cheetah	Fillauer All-Pro
F	27	1.71	56.7	Trauma	42	Össur Cheetah X-treme	Össur Cheetah X-plore
M	31	1.87	78.6	Trauma	102	Freedom Innovations Catapult	Fillauer All-Pro
M	26	1.82	78.8	Trauma	29	Endolite Blade XT	Freedom Innovations Silhouette
F	48	1.68	70.4	Trauma	126	Fillauer RSP	Össur Proflex
M	45	1.83	77.3	Trauma	420	Össur FlexRun	Freedom Innovations Renegade
M	29	1.89	86.9	Trauma	80	Cheetah X-plore	Ohio Willow Wood Pathfinder II
M	32	1.77	82.5	Trauma	96	Össur FlexRun	Freedom Innovations Renegade
M	67	1.83	81.7	Trauma	516	Freedom Innovations Catapult	Freedom Innovations Renegade
Mean Values							
TTA							
5F/8M	34.8 ± 12.5	1.76 ± 0.08	72.0 ± 12.6		164		
No TTA							
5F/8M	32.8 ± 11.8	1.74 ± 0.08	74.1 ± 10.3		N/A		

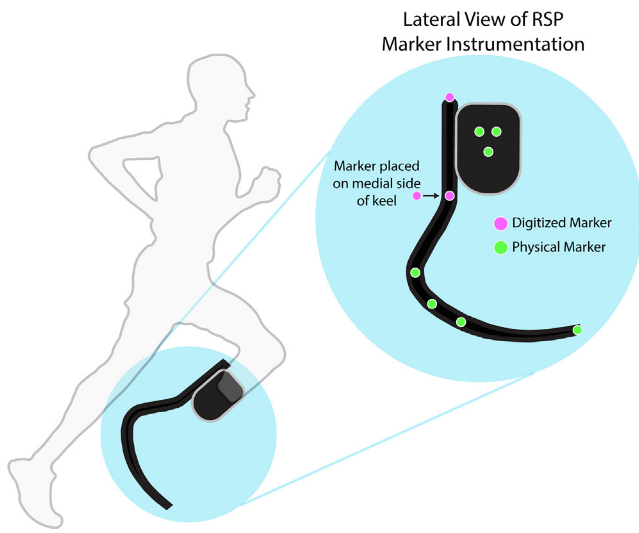

Fig. 1. Running-specific prosthesis marker orientation - lateral view. Digitized markers are established relative to the cluster of physical markers on the RSP socket.

post-hoc pairwise comparisons when significant main or interaction effects were found (α=0.05). The ANOVAs used for comparison incorporated unbalanced designs (Kuznetsova et al., 2017).

3. Results

Some individuals could not complete all conditions of the protocol. One participant using a DUP could not complete trials at 4.0 m/s and three participants using DUPs could not complete trials at 5.0 m/s. In addition, two participants could not complete trials at 5.0 m/s while using their RSP.

3.1. Vertical GRFs

There were significant main effects of side and speed, and a significant effect of prosthesis condition when comparing DUPs and RSPs (Table 3). There were also significant prosthesis condition × side interaction effects (Table 3). No differences in peak vertical ground reaction force (vGRF) emerged between people with and without TTA. For the DUP condition, no differences were observed in peak vGRF between the amputated and intact legs; however, peak vGRF was greater for the intact leg compared to amputated leg of the RSP at every speed (Fig. 2, Table 4). In addition, at higher speeds (4.0 m/s and 5.0 m/s) the amputated leg of the DUP had greater peak vGRF compared to the amputated leg of the RSP ($p \leq 0.02$).

3.2. Propulsive/Braking GRFs

Peak propulsive/braking GRFs had significant main effects of side, speed, and prosthesis condition, except when comparing RSP vs. no TTA. There were multiple significant interaction effects (Table 3).

Peak propulsive force in the intact leg for both prosthesis conditions did not differ from people without TTA, however, the amputated leg in both prosthesis conditions had smaller peak propulsive force compared to people without TTA at all speeds ($p < 0.01$) except for the RSP at 2.5 m/s. Peak propulsive GRFs were greater for the intact leg compared to amputated leg in both prosthesis conditions at all speeds, except for the RSP condition at 2.5 m/s ($p < 0.01$) (Fig. 2, Table 4). In addition, peak propulsive GRFs were greater in the amputated leg for people with TTA using RSPs compared to DUPs at all speeds ($p < 0.01$).

Peak braking force was greater for people without TTA compared to the amputated leg using DUPs and RSPs at all speeds (Fig. 2, Table 4). People with TTA had a smaller amputated leg peak braking force compared to the intact leg for both prostheses ($p < 0.01$), however, this force did not differ in the amputated leg between devices.

3.3. Medial/Lateral GRFs

Significant main effects for side and speed were observed for peak medial and lateral GRFs (Table 3). There was a significant main effect of prosthesis condition for lateral (DUP vs. no TTA) and medial (DUP vs. no TTA and RSP vs. DUP) GRFs. Significant interaction effects were also observed (Table 3). The amputated leg of people wearing RSPs generated a smaller peak medial GRF compared to people without TTA at every speed except for 3.5 m/s ($p < 0.01$). Medial GRFs on the amputated leg were smaller in runners with TTA when using RSPs compared to DUPs at 4.0 m/s and 5.0 m/s ($p \leq 0.02$), and smaller than the intact leg at every speed ($p < 0.01$) (Fig. 2, Table 4). The intact leg of people wearing DUPs generated greater medial GRFs compared to the amputated leg at 3.5–5.0 m/s ($p < 0.01$). Medial GRFs increased with speed for the intact leg of people with TTA ($p < 0.01$), but not for people without TTA or for the amputated legs.

People wearing RSPs had smaller lateral GRFs in the amputated leg compared to people without TTA at 3.0–5.0 m/s ($p \leq 0.05$) (Table 4). When wearing DUPs, the amputated leg generated smaller lateral GRFs compared to people without TTA and compared to the intact leg at 5.0 m/s ($p \leq 0.03$) (Fig. 2, Table 4). The amputated leg of people with TTA wearing RSPs did not consistently increase peak lateral GRFs with each increase in speed, but values at the slowest speed were smaller than at the fastest speed (Fig. 2). Peak lateral GRFs increased with speed for people without TTA, for the intact legs of people with TTA, and for the amputated leg of people wearing DUPs between the slower speeds (2.5 m/s, 3.0 m/s, 3.5 m/s) and the fastest speed (5.0 m/s).

Table 2
Explanation of statistical design. Post-hoc pairwise comparisons (paired or unpaired as appropriate) were performed using Tukey's adjustment for multiple comparisons when significant main or interaction effects were found.

ANOVA	Dependent Variable	Within-subject factors	Between-subject factors
DUP vs. No TTA	Joint work or GRF	• **Speed:** 5 levels (2.5 m/s, 3.0 m/s, 3.5 m/s, 4.0 m/s, 5.0 m/s) • **Side**: 2 levels (R/Intact vs. L/Amputated)	• **Prosthesis Condition:** 2 levels (Person with TTA using DUP/Person without TTA)
RSP vs. No TTA	Joint work or GRF	• **Speed:** 5 levels (2.5 m/s, 3.0 m/s, 3.5 m/s, 4.0 m/s, 5.0 m/s) • **Side:** 2 levels (R/Intact vs. L/Amputated)	• **Prosthesis Condition:** 2 levels (Person with TTA using RSP/Person without TTA)
DUP vs. RSP	Joint work or GRF	• **Speed:** 5 levels (2.5 m/s, 3.0 m/s, 3.5 m/s, 4.0 m/s, 5.0 m/s) • **Prosthesis Condition**: 2 levels (RSP/DUP) • **Side:** 2 levels (Intact vs. Amputated)	None

Table 3
Main and interaction effects of three-dimensional peak ground reaction forces.

	DUP vs. No TTA	DUP vs. RSP	RSP vs. No TTA
	VERTICAL		
Speed	<0.01	<0.01	<0.01
Side	<0.01	<0.01	<0.01
Prosthesis Condition	–	<0.01	–
Interactions	Prosthesis Condition × Side (<0.01)	Prosthesis Condition × Side (<0.01)	Prosthesis Condition × Side (<0.01)
	PROPULSIVE		
Speed	<0.01	<0.01	<0.01
Side	<0.01	<0.01	<0.01
Prosthesis Condition	<0.01	<0.01	–
Interactions	Prosthesis Condition × Side (<0.01)	Prosthesis Condition × Side (<0.01)	Prosthesis Condition × Side (<0.01)
	Prosthesis Condition × Speed (<0.01)	Side × Speed (<0.01)	
	Side × Speed (<0.01)		
	Prosthesis Condition × Speed × Side (<0.01)		
	BRAKING		
Speed	<0.01	<0.01	<0.01
Side	<0.01	<0.01	<0.01
Prosthesis Condition	<0.01	<0.01	–
Interactions	Prosthesis Condition × Side (<0.01)	Prosthesis Condition × Side (<0.01)	Prosthesis Condition × Side (<0.01)
	Prosthesis Condition × Speed (0.04)	Side × Speed (<0.01)	
	Side × Speed (<0.01)		
	Prosthesis Condition × Speed × Side (<0.01)		
	LATERAL		
Speed	<0.01	<0.01	<0.01
Side	<0.01	<0.01	<0.01
Prosthesis Condition	0.04	–	–
Interactions	–	Prosthesis Condition × Side (<0.01)	Prosthesis Condition × Side (<0.01)
		Side × Speed (<0.01)	
	MEDIAL		
Speed	<0.01	<0.01	<0.01
Side	0.02	<0.01	<0.01
Prosthesis Condition	<0.01	<0.01	–
Interactions	Prosthesis Condition × Side (<0.01)	Prosthesis Condition × Side (<0.01)	Prosthesis Condition × Side (<0.01)
	Prosthesis Condition × Speed (0.04)	Side × Speed (<0.01)	Side × Speed (0.03)

3.4. Hip work

There were significant main effects of speed in positive and negative hip work (Table 5). A significant main effect of side was present for positive hip work except when comparing RSP vs. no TTA (Table 5). There was a significant main effect of prosthesis condition for positive and negative hip work when comparing RSPs vs. DUPs. A significant interaction effect of side × prosthesis condition ($p < 0.01$) was found for positive hip work when comparing DUP vs. no TTA and DUP vs. RSP (Table 5). The amputated leg of people wearing DUPs had greater positive hip work at 4.0 m/s compared to the intact leg, and greater positive hip work at 3.5 m/s and 5.0 m/s when compared to people wearing RSPs ($p \leq 0.04$) (Fig. 3, Table 6). Positive hip work increased with increasing speed for DUPs and from 2.5 m/s to 4.0 m/s for RSPs, but not for people without TTA. Negative hip work increased with speed in the intact leg for both DUPs and RSPs, the amputated leg for RSPs, and for people without a TTA.

3.5. Knee work

There were significant main effects of side for positive and negative knee work ($p \leq 0.01$, Table 5). There was a significant main effect of speed for DUP vs. no TTA (positive and negative knee work) and RSP vs. no TTA (negative knee work) ($p \leq 0.01$). Significant main effects of prosthesis condition were observed for RSP vs. DUP (positive knee work) and DUP/RSP vs. no TTA (negative knee work, $p < 0.01$) (Table 5). Significant side × prosthesis condition interaction effects were observed for positive and negative knee work, except for RSP vs. DUP (positive knee work). There was a significant side × speed interaction effect for negative knee work (RSP vs. no TTA and DUP vs. no TTA) (Table 5).

The intact side knee had greater positive knee work compared to the amputated side at all speeds for RSPs, and at 2.5 m/s, 3.0 m/s, and 3.5 m/s for DUPs ($p < 0.01$) (Fig. 3, Table 6). The amputated side knee of people wearing RSPs had smaller positive knee work compared to the amputated side knee of people wearing DUPs and compared to people without TTA at all speeds except for 5.0 m/s ($p < 0.02$). The amputated side knee for people with TTA had smaller negative knee work compared to the intact side and people without TTA at all speeds, regardless of prosthesis type ($p < 0.01$). The intact side knee of people wearing DUPs had smaller negative work compared to people without TTA at 5.0 m/s ($p < 0.01$) (Fig. 3, Table 6).

3.6. Ankle work

There were significant main effects of side, speed, and prosthesis condition for positive and negative "ankle" work for people with and without TTA ($p < 0.01$, Table 5), except for the effect of prosthesis condition in negative ankle work of people wearing DUPs/RSPs vs. no TTA and positive ankle work of people wearing RSPs compared to people without TTA. A significant interaction of side × prosthesis condition was observed except for negative ankle work of DUP vs. no TTA (Table 5).

The DUP had smaller positive ankle work compared to the intact leg, the RSP, and people without TTA ($p < 0.01$) (Fig. 3, Table 6). Intact legs of people with TTA and people without TTA increased positive ankle work with running speed, but the amputated leg did not increase ankle work with speed, regardless of prosthesis condition. Negative ankle work was greater in the RSP compared to the DUP at all speeds except 5.0 m/s ($p \leq 0.02$). Negative work was greater in the RSP compared to the intact leg at speeds <5.0 m/s ($p \leq 0.05$). However, negative work did not change

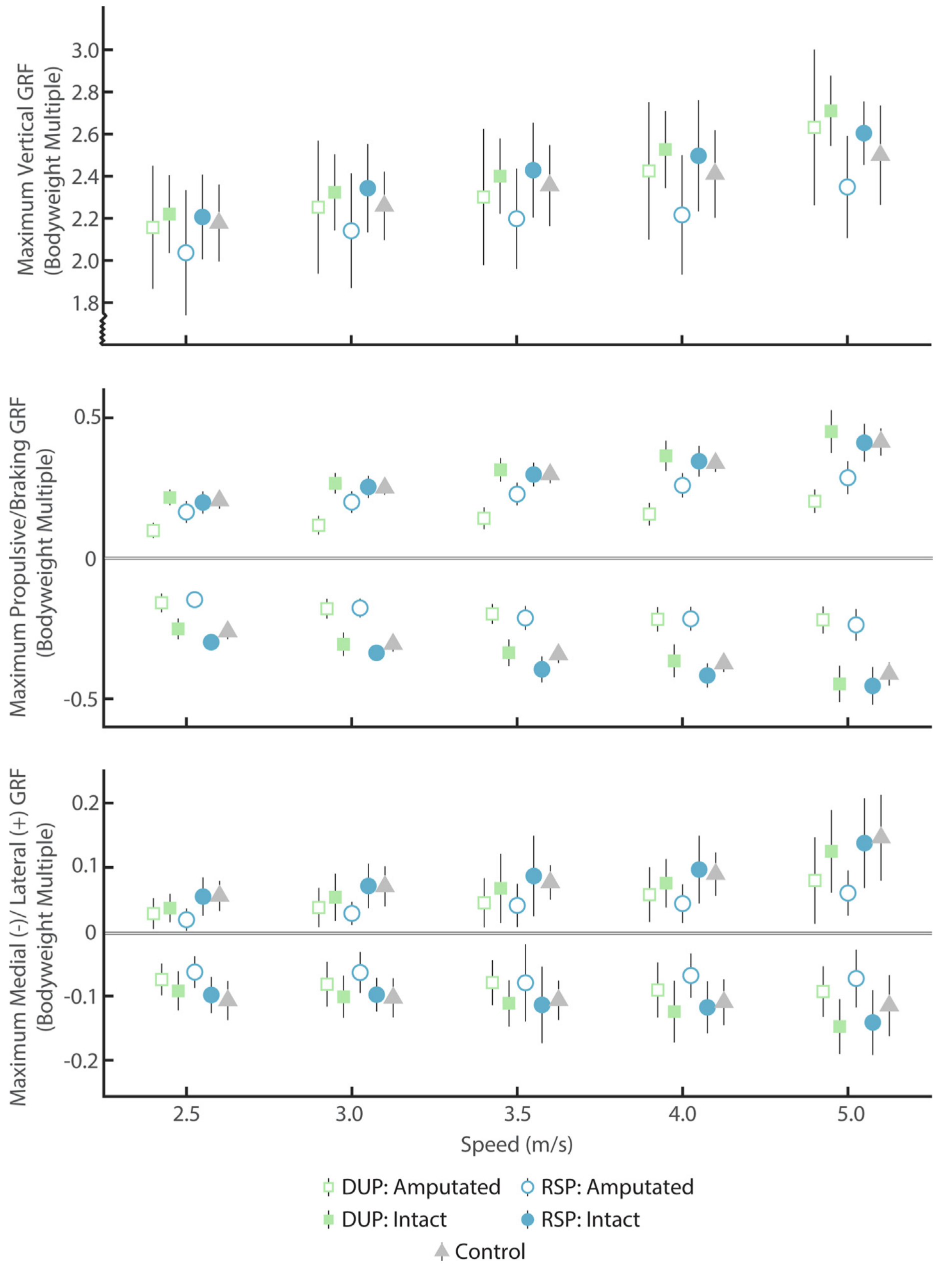

Fig. 2. Peak vertical, anterior/posterior, and medial/lateral GRFs at running speeds ranging from 2.5 m/s to 5.0 m/s for people with TTA wearing RSPs and DUPs in addition to people without TTA. Vertical lines indicate the standard deviation across participants. Note the different vertical scales for each GRF component. Data points are offset at each speed for legibility.

with increasing running speed while using the RSP. Negative ankle work magnitude increased with running speed for people without TTA and for intact legs.

4. Discussion

The purpose of this study was to characterize how (1) presence of an amputation, (2) the use of an RSP compared to a DUP and (3) running speed affect GRFs and stance phase joint work during running. These measures are important in assessing joint function, especially in people with TTA, who have limited push-off power from passive prostheses. Changes in joint work and GRFs reflect movement adaptations to prostheses and the lack of muscles crossing the ankle joint. Consistent with our expectations, we observed differing joint work and GRFs between people with and without TTA and between the intact and amputated legs for people with TTA. RSPs produced greater positive work, indicating greater energy return than DUPs at every speed; however, hip work, not device work, increased with speed for people with TTA.

4.1. Effect of amputation

Consistent with our expectations, people with TTA had smaller braking and propulsive GRFs in the amputated leg compared to the intact leg or a person without TTA, regardless of prosthesis type (Fig. 2). Furthermore, people with TTA had differences in peak vGRFs between legs, which may contribute to long-term joint degeneration (Gailey et al., 2008; Norvell et al., 2005), whereas peak vGRFs were similar between legs for people without TTA. Smaller propulsive forces in people with TTA are not surprising

Table 4
Average (standard deviation) peak three-dimensional ground reaction forces for people with TTA running using RSPs and DUPs and for people without TTA running at 2.5–5.0 m/s in bodyweights. Significant differences compared to intact side are denoted by '*'. Significant differences compared to the amputated leg of people wearing DUPs are denoted by '○'. Significant differences compared to the control leg are denoted by '▲'. $\alpha \leq 0.05$ for all comparisons.

Speed (m/s)	RSP AMP	RSP IN	DUP AMP	DUP IN	CONTROL
	VERTICAL				
2.5	2.050(0.301)*	2.228(0.215)	2.157(0.292)	2.220(0.184)	2.182(0.186)
3.0	2.150(0.302)*	2.352(0.185)	2.253(0.293)	2.324(0.182)	2.259(0.183)
3.5	2.205(0.301)*	2.434(0.181)	2.301(0.290)	2.422(0.164)	2.351(0.180)
4.0	2.225(0.300)*○	2.506(0.195)	2.425(0.287)	2.527(0.166)	2.407(0.183)
5.0	2.353(0.293)*○	2.622(0.180)	2.632(0.288)	2.710(0.163)	2.490(0.178)
	PROPULSIVE				
2.5	0.162(0.038)○	0.198(0.042)	0.099(0.027)*▲	0.216(0.028)	0.206(0.034)
3.0	0.196(0.044)*○▲	0.250(0.042)	0.118(0.029)*▲	0.267(0.026)	0.251(0.032)
3.5	0.225(0.045)*○▲	0.293(0.038)	0.142(0.033)*▲	0.315(0.026)	0.294(0.034)
4.0	0.255(0.044)*○▲	0.341(0.053)	0.157(0.033)*▲	0.365(0.034)	0.336(0.036)
5.0	0.283(0.042)*○▲	0.408(0.060)	0.203(0.034)*▲	0.451(0.037)	0.405(0.042)
	BRAKING				
2.5	−0.150(0.026)*▲	−0.301(0.027)	−0.159(0.033)*▲	−0.251(0.037)	−0.262(0.029)
3.0	−0.181(0.025)*▲	−0.341(0.035)	−0.180(0.033)*▲	−0.306(0.039)	−0.305(0.032)
3.5	−0.207(0.030)*▲	−0.388(0.033)	−0.198(0.033)*▲	−0.336(0.043)	−0.344(0.033)
4.0	−0.220(0.035)*▲	−0.421(0.026)	−0.217(0.032)*▲	−0.365(0.047)	−0.373(0.036)
5.0	−0.241(0.037)*▲	−0.457(0.026)	−0.219(0.033)*▲	−0.447(0.044)	−0.423(0.038)
	MEDIAL				
2.5	−0.061(0.024)*▲	−0.103(0.029)	−0.074(0.025)▲	−0.092(0.030)	−0.096(0.029)
3.0	−0.062(0.023)*▲	−0.100(0.029)	−0.082(0.024)	−0.101(0.030)	−0.094(0.029)
3.5	−0.067(0.023)*	−0.106(0.028)	−0.079(0.024)*▲	−0.111(0.031)	−0.096(0.029)
4.0	−0.066(0.022)*○▲	−0.119(0.028)	−0.091(0.025)*	−0.124(0.032)	−0.102(0.029)
5.0	−0.070(0.023)*○▲	−0.144(0.028)	−0.093(0.025)*	−0.148(0.033)	−0.110(0.027)
	LATERAL				
2.5	0.021(0.017)*	0.053(0.031)	0.028(0.024)	0.037(0.022)	0.061(0.028)
3.0	0.030(0.018)*▲	0.069(0.031)	0.037(0.024)	0.054(0.022)	0.076(0.029)
3.5	0.037(0.0018)*▲	0.071(0.027)	0.045(0.024)	0.067(0.021)	0.083(0.029)
4.0	0.045(0.018)*▲	0.095(0.027)	0.058(0.024)	0.075(0.020)	0.098(0.029)
5.0	0.063(0.018)*▲	0.135(0.026)	0.079(0.024)*▲	0.125(0.021)	0.157(0.027)

as the ankle plantarflexor muscles are largely responsible for the propulsion of the body center of mass during running (Hamner et al., 2010), and passive prostheses cannot generate similar propulsion. To assist in propelling the body, people with TTA have greater amputated side positive hip work during walking (Silverman et al., 2008) and running with DUPs (Czerniecki et al., 1991), like our results. People using DUPs had greater amputated side positive hip work compared to the intact side (4.0 m/s) and compared to the leg of people without TTA (3.5 m/s and 5.0 m/s) (Fig. 3). Using RSPs reduced the inter-limb positive hip work differences compared to DUPs, although there was large variability in hip work across participants.

4.2. Effect of prosthesis type

DUPs and RSPs differ in their mechanical response to load, which influences GRF generation and joint mechanics. The geometry and stiffness characteristics of the RSP are designed to facilitate energy storage and return, which assisted in generating greater propulsive GRFs and positive prosthesis work thus mitigating compensatory hip work compared to DUPs. The energy storage and return characteristics of the RSP make them well-suited for highly-dynamic tasks, like running, where forward propulsion is critical.

Running with RSPs resulted in smaller peak vGRFs in the amputated leg compared to using DUPs, which was consistent with our expectations. Greater compliance of the RSP results in smaller vertical GRF generation compared to stiffer prostheses (Hafner et al., 2002; Nolan, 2008). Our results are consistent with previous studies that have shown smaller vGRFs in the amputated leg compared to the intact leg while running with RSPs (Fig. 2, Table 4) (Baum et al., 2016; Grabowski et al., 2010). However, no differences in peak vGRF between amputated and intact legs were observed for people with TTA wearing DUPs. Understanding vGRFs in people with TTA is important in relation to potential injury development. Some have identified peak vGRF differences between legs in people with TTA (Prince et al., 1992; Sanderson and Martin, 1996) while others have contrary results (Engsberg et al., 1992). In our results, vGRFs were similar between legs for people wearing DUPs, however peak vGRFs were higher while using DUPs compared to using RSPs at 4.0 m/s and 5.0 m/s. Asymmetric vGRFs for people wearing RSPs may increase the risk for joint degeneration as inter-limb joint loading differences are a risk-factor for the development of osteoarthritis (Lloyd et al., 2010; Gailey et al., 2008). However, smaller forces may be beneficial for long-term joint health in the amputated leg, as over time, higher peak forces lead to greater cumulative load effects (Miller, 2017).

Greater vertical and smaller propulsive GRFs while using DUPs indicates better vertical support at the expense of decreased propulsion from the device. In contrast, compliant prostheses increase forward propulsion at the expense of reduced body support (Fey et al., 2011). The reduced vertical support and greater compliance from the RSP may require a more extended limb posture and associated reduction in knee power and work during stance phase compared to using DUPs, which has been previously observed during running (Sanderson and Martin, 1996). Muscle activity and force analyses should be performed to identify contributions of individual muscles, prostheses and skeletal structure to body support and propulsion for people with TTA to further investigate this adaptation (e.g., Hamner et al., 2010; Fey et al., 2013).

Running with RSPs resulted in smaller medial/lateral GRFs in the amputated side compared to the intact side (Fig. 2) at all speeds. DUPs may improve medial/lateral force generation compared to RSPs given that DUPs are used with components that can affect ground contact, such as foot shells and shoes. Smaller ranges of medial/lateral GRFs have been observed in runners with

Table 5
Main and interaction effects of positive and negative joint work.

	HIP WORK		
	DUP vs. No TTA	DUP vs. RSP	RSP vs. No TTA
		Positive	
Speed	<0.01	<0.01	<0.01
Side	<0.01	0.01	–
Prosthesis Condition	–	<0.01	
Interactions	Side × Prosthesis Condition (<0.01)	Side × Prosthesis Condition (0.02)	–
		Negative	
Speed	<0.01	<0.01	<0.01
Side	–	–	–
Prosthesis Condition	–	<0.01	–
Interactions	–	–	–
	KNEE WORK		
		Positive	
Speed	<0.01	–	–
Side	<0.01	<0.01	<0.01
Prosthesis Condition	–	<0.01	–
Interactions	Side × Prosthesis Condition (<0.01)	–	Side × Prosthesis Condition (<0.01)
		Negative	
Speed	<0.01	–	<0.01
Side	<0.01	<0.01	<0.01
Prosthesis Condition	<0.01	–	<0.01
Interactions	Side × Speed (<0.01) Side × Prosthesis Condition (<0.01)	Side × Prosthesis Condition (<0.01)	Side × Speed (<0.01) Side × Prosthesis Condition (<0.01)
	ANKLE WORK		
		Positive	
Speed	<0.01	<0.01	<0.01
Side	<0.01	<0.01	<0.01
Prosthesis Condition	<0.01	<0.01	–
Interactions	Side × Prosthesis Condition (<0.01)	Side × Prosthesis Condition (<0.01)	Side × Prosthesis Condition (0.02)
		Negative	
Speed	<0.01	<0.01	<0.01
Side	0.04	<0.01	<0.01
Prosthesis Condition	–	<0.01	–
Interactions	–	Side × Prosthesis Condition (<0.01)	Side × Prosthesis Condition (<0.01)

TTA using RSPs (Baum et al., 2016) and contribute to a greater range of whole-body angular momentum (Sepp et al., 2019), which is related to challenges in balance regulation (Herr and Popovic, 2008). Future RSP designs may benefit from features that better modulate medial/lateral GRFs to facilitate running on uneven surfaces like roads or trails.

4.3. Effect of speed

Increases in running speed are associated with greater joint loading, joint work, and GRFs (Keller et al., 1996; Novacheck, 1998) as muscular demand increases, which was reflected in our results. We also observed increases in positive joint work at the hip (all conditions and legs) and ankle (intact ankle and ankle of people without TTA) with speed for people with and without TTA. Prosthesis work was not affected by speed, and positive knee work only increased from the slowest speeds (2.5 m/s, 3.0 m/s) compared to the fastest speed (5.0 m/s) for the intact leg of people wearing DUPs (Table 6). Increases in ankle work for people without TTA and for the intact leg of people with TTA with speed indicate

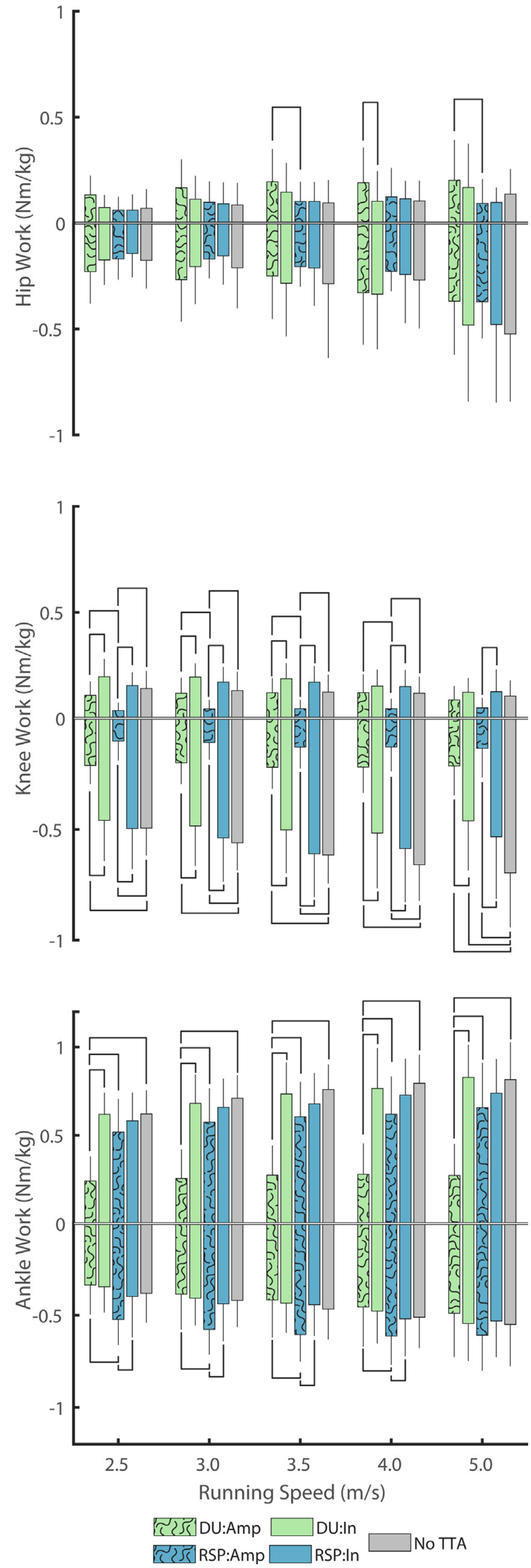

Fig. 3. Average positive and negative work of the ankle, knee, and hip during stance phase of running at five speeds for people with TTA wearing DUPs and RSPs in addition to people without TTA. Vertical lines indicate the standard deviation across participants and brackets indicate significant differences between prosthesis conditions and the amputated and intact legs ($p \leq 0.05$).

Table 6
Average (standard deviation) positive and negative joint work for people with TTA wearing RSPs and DUPs and for people without TTA while running at speeds 2.5–5.0 m/s. Pairwise comparisons of effect of side/device within each speed. '*' indicates difference between amputated and intact legs. '○' indicates difference between amputated legs of RSPs and DUPs. '▲' indicates difference compared to people without TTA. $\alpha \le 0.05$ for all comparisons.

	Positive Hip Work				
Speed (m/s)	RSP AMP	RSP IN	DUP AMP	DUP IN	CONTROL
2.5	0.062(0.063)	0.062(0.074)	0.134(0.091)	0.074(0.059)	0.070(0.090)
3.0	0.099(0.099)	0.092(0.101)	0.167(0.134)	0.113(0.111)	0.086(0.105)
3.5	0.104(0.092)○	0.103(0.092)	0.196(0.154)	0.147(0.138)	0.096(0.107)
4.0	0.124(0.136)	0.115(0.085)	0.191(0.166)*	0.103(0.143)	0.105(0.096)
5.0	0.093(0.115) ○	0.098(0.070)	0.202(0.191)	0.169(0.206)	0.137(0.119)
	Negative Hip Work				
2.5	−0.169(0.098)	−0.144(0.113)	−0.230(0.151)	−0.174(0.118)	−0.176(0.133)
3.0	−0.170(0.091)	−0.155(0.136)	−0.268(0.198)	−0.206(0.178)	−0.212(0.192)
3.5	−0.203(0.094)	−0.213(0.179)	−0.250(0.204)	−0.284(0.251)	−0.287(0.350)
4.0	−0.228(0.094)	−0.243(0.229)	−0.329(0.245)	−0.336(0.261)	−0.269(0.228)
5.0	−0.372(0.173)	−0.479(0.367)	−0.369(0.253)	−0.482(0.362)	−0.524(0.319)
	Positive Knee Work				
2.5	0.036(0.037)*○▲	0.154(0.064)	0.108(0.066)*	0.196 (0.084)	0.141(0.083)
3.0	0.044(0.042)*○▲	0.171(0.072)	0.118(0.074)*	0.195(0.064)	0.131(0.089)
3.5	0.045(0.041)*○▲	0.170(0.075)	0.120(0.069)*	0.187(0.074)	0.124(0.082)
4.0	0.046(0.047)*○▲	0.150(0.078)	0.121(0.087)	0.152(0.077)	0.119(0.077)
5.0	0.049(0.047)*	0.126(0.105)	0.087(0.066)	0.123(0.068)	0.105(0.073)
	Negative Knee Work				
2.5	−0.099(0.088)*▲	−0.494(0.184)	−0.210(0.084)*▲	−0.458(0.183)	−0.493(0.123)
3.0	−0.106(0.078)*▲	−0.537(0.198)	−0.198(0.096)*▲	−0.483(0.180)	−0.559(0.125)
3.5	−0.127(0.098)*▲	−0.609(0.196)	−0.218(0.097)*▲	−0.501(0.196)	−0.614(0.129)
4.0	−0.126(0.109)*▲	−0.585(0.242)	−0.217(0.116)*▲	−0.515(0.250)	−0.658(0.164)
5.0	−0.132(0.132)*▲	−0.532(0.282)	−0.212(0.133)*▲	−0.460(0.224) ▲	−0.695(0.246)
	Positive Ankle Work				
2.5	0.518(0.188)○	0.583(0.160)	0.241(0.139)*▲	0.619(0.123)	0.621(0.134)
3.0	0.574(0.192)○	0.659(0.162)	0.256(0.163)*▲	0.681(0.164)	0.710(0.131)
3.5	0.605(0.199)○	0.678(0.175)	0.274(0.169)*▲	0.734(0.180)	0.759(0.142)
4.0	0.619(0.214)○	0.728(0.206)	0.279(0.175)*▲	0.765(0.229)	0.795(0.162)
5.0	0.657(0.253)○	0.738(0.194)	0.273(0.178)*▲	0.828(0.185)	0.816(0.212)
	Negative Ankle Work				
2.5	−0.523(0.138)*○	−0.390(0.221)	−0.337(0.160)	−0.346(0.139)	−0.381(0.159)
3.0	−0.577(0.137)*○	−0.438(0.203)	−0.386(0.193)	−0.407(0.148)	−0.420(0.144)
3.5	−0.606(0.146)*○	−0.443(0.168)	−0.417(0.204)	−0.435(0.161)	−0.467(0.165)
4.0	−0.613(0.158)*○	−0.519(0.204)	−0.455(0.216)	−0.478(0.176)	−0.511(0.167)
5.0	−0.608(0.193)	−0.532(0.195)	−0.490(0.236)	−0.545(0.204)	−0.550(0.226)

the importance of the plantarflexors to run faster (Fig. 3). Increases in hip work, but not device work, with faster speeds highlight the hip as the main mechanism for running speed modulation in people with TTA.

Positive hip work was reduced when using RSPs, and some participants achieved faster running speeds using their RSP during the experimental protocol. Thus using RSPs instead of DUPs may enable people to increase their top running speed while reducing compensatory hip demands. However, at the highest speeds (4.0 m/s and 5.0 m/s), RSPs returned more energy than they stored (Fig. 3), which should be noted as an important limitation. Net positive work from passive devices is not possible, and thus our findings highlight the need for more detailed RSP models. While our marker set aimed to capture full device deflection, a relatively limited marker number and rigid body assumptions may not reliably capture the full deformation of the RSP, thus affecting power calculations. The J-shaped RSPs may be affected more by this limitation compared to the C-shape RSPs due the lack of markers on the prosthesis proximal to the most acute point of curvature (Fig. 1) and large device deflection in this region. As faster running speeds were achieved, RSPs deflected more, which likely was not fully captured by our instrumentation. Little data exist quantifying RSP energy storage and return for a range of speeds, however a previous study of two transtibial amputees found overall approximately 100% RSP efficiency (>100% under specific conditions) at top speed (ranging from 6.81 to 7.05 m/s) (Buckley, 2000). Our results were similar to the aforementioned study at top speeds, in which a small marker set was also used (Buckley, 2000). Future RSP models should account for detailed device deflection, similar to recently developed finite-element models (Rigney et al., 2015; Rigney et al., 2017). Experimental protocols should also be modified to capture deflection along the entire length of the RSP in future work.

Variation in prosthesis design is a potential limitation of the study. DUP designs varied across participants (Table 1) and may influence energy storage and return and joint mechanics. RSPs also varied in design; however, DUP design variation is likely more important as DUPs had various toe designs, geometries, and associated footwear. RSP shape was evenly distributed across the study participants and varied less in overall design. This study design eliminated the confounding factor of acclimation to the device and help to make the results more generalizable to the overall population of people with TTA.

5. Conclusion

Prostheses enable mobility for people with TTA, but differences in device characteristics influence their ability to restore function. Regardless of prosthesis type, people with TTA had reduced propulsive and braking GRFs in addition to asymmetric hip work. The use of a DUP increased average peak loading between legs at faster running speeds but using an RSP resulted in asymmetric vGRF loading. The use of a DUP improved vertical support, but at the expense of propulsive GRF generation. Using an RSP also reduced medial/lateral GRF generation and reduced inter-limb hip work differences. Hip work, and not device work, was the main mechanism to increase speed for people with TTA.

Reducing barriers to access RSPs for people with TTA enables them to freely participate in physical activity. Using RSPs may be especially beneficial for faster running speeds and device designs that improve medial/lateral force generation have potential positive implications for balance regulation in recreational runners. Future work should investigate neuromuscular control patterns for people with TTA in addition to comprehensive analysis of joint contact loading, providing further insight into movement adaptations and injury risk in this population.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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