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Trunk Movement Compensations and Corresponding Core Muscle Demand during Step Ambulation in People with Unilateral Transtibial Amputation

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Abstract

The objective of this investigation was to identify demands from core muscles that corresponded with trunk movement compensations during bilateral step ambulation in people with unilateral transtibial amputation (TTA). Trunk rotational angular momentum (RAM) was measured using motion capture and bilateral surface EMG was measured from four bilateral core muscles during step ascent and descent tasks in people with TTA and healthy controls. During step ascent, the TTA group generated larger mediolateral ($P = 0.01$) and axial ($P = 0.01$) trunk RAM toward the leading limb when stepping onto the intact limb than the control group, which corresponded with high demand from the bilateral erector spinae and oblique muscles. During step descent, the TTA group generated larger trunk RAM in the sagittal ($P < 0.01$), frontal ($P < 0.01$), and transverse planes ($P = 0.01$) than the control group, which was an effect of falling onto the intact limb. To maintain balance and arrest trunk RAM, core muscle demand was larger throughout the loading period of step descent in the TTA group. However, asymmetric trunk movement compensations did not correspond to asymmetric core muscle demand during either task, indicating a difference in motor control compensations dependent on the leading limb.

Keywords

Dysvascular transtibial amputation; core muscle demand; trunk movement compensations; high-demand tasks

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Conflict of Interest

None.

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1. Introduction

Rehabilitation following transtibial amputation (TTA) aims to maximize functional independence by retraining movement patterns during gait to lower the risk of secondary overuse injuries, such as low back pain (LBP) (Cutson and Bongiorno 1996). Although the underlying mechanisms behind the development of LBP following amputation remains idiopathic, asymmetric trunk movement patterns are known to increase the risk of LBP (Kumar 2001; McGill 2007). Trunk movement asymmetry during gait is often associated with asymmetric core muscle demand, which can indicate poor control of the trunk muscles (Tsao et al. 2008).

Muscle demand is associated with the net joint moments during gait, which represent the net agonist and antagonist muscle activity spanning joints (Winter 1984; Sanderson and Martin 1997; Powers et al. 1998; Bateni and Olney 2002). Thus, clinicians target interventions to minimize asymmetric trunk compensations adopted in the absence of ankle plantarflexion after TTA. However, rehabilitation in people with dysvascular TTA is exceedingly complex due to common neurovascular comorbidities and poor physical health (Cutson and Bongiorno 1996), which compounds the risk of LBP (Shiri et al. 2010).

To achieve independence of mobility, people with TTA must daily perform high-demand functional tasks that increase the demand on the musculoskeletal system compared to level-ground walking, such as step ambulation (Nadeau et al., 2003; De Laat et al., 2013). To maximize early functional recovery, people with TTA may initially adopt a movement pattern ascending steps by leading with the intact limb and descend steps leading with the amputated limb (Schmalz et al. 2007; Barnett et al. 2014). Even when rehabilitation has completed, habitual disuse of the amputated limb may continue. In addition, during both step ascent and descent, people with TTA typically adopt a “quadriceps avoidance” strategy, which improves trunk and pelvic stability, and has been linked with a forward trunk lean (although not directly measured) (Schmalz et al., 2007). We recently associated changes in trunk kinematics with large low back internal extension moments in people with TTA compared to healthy participants during step ambulation (Murray et al. 2017). However, the muscle demand resulting from trunk movement compensations during stepping tasks after TTA remains unknown. In addition, it is unknown if motor control patterns, as evidenced by muscle activation patterns, differs when leading with intact versus amputated limbs during stepping tasks.

We previously quantified asymmetric trunk movement compensations in people with TTA using segmental angular momentum during walking (Gaffney et al. 2016). Through Newton-Euler mechanics, momentum is embedded within the three common descriptors of human movement (kinematics, kinetics, and neuromuscular control) (Gaffney et al. 2017). We have used RAM to describe movement compensations in patients with TTA because it provides a measure that is clinically interpretable and more sensitive than traditional observational analyses, which lacks sensitivity and standardization (Coutts 1999; Toro et al. 2003; Shull et al. 2014), particularly when assessing movement in the lumbopelvic region outside of level walking. Patients with TTA generated larger amount of trunk RAM during over ground walking, which is dependent upon the angular velocity of that segment, and associated to a

change in segment position (i.e. range of motion). Through the inclusion of speed and mass, and because segmental RAM is foundational in joint moments calculated via inverse dynamics (Gaffney et al. 2017), which represent the net effect of all agonist and antagonist muscle activity spanning a joint, we interpreted our previous findings of larger asymmetric generation of segmental RAM to potentially correspond with movement strategies that result in high asymmetric eccentric muscle demand needed to arrest segmental momentum. However, it is not clear that asymmetric generation of momentum corresponds with asymmetric muscle demand. Furthermore, it is unknown how asymmetric movements quantified using segmental RAM correspond to muscle demand during stepping tasks, which are more difficult than level-ground walking for this population.

The primary objective of this investigation was to identify demands from core trunk/pelvis muscles (bilateral erector spinae, external oblique, gluteus maximus, and gluteus medius) that correspond with trunk movement compensations, quantified with segmental RAM, during step ascent and descent in people with unilateral TTA. The secondary objective was to establish if asymmetric movements (trunk RAM that is asymmetric and different than that of the HC group) corresponded with asymmetric core muscle demand. We hypothesized that trunk movement compensations adopted by people with TTA would correspond with higher muscle demand than seen in healthy individuals with symmetrical trunk movement. We also hypothesized that differences across limbs in the TTA group would identify motor control patterns that were habituated following amputation.

2. Methods

2.1 Participants

Ten male participants with unilateral dysvascular TTA and ten male healthy control (HC) participants were enrolled (Table 1). Eligibility criteria included: BMI $\leq 40 \text{ kg/m}^2$; age: 50–85 years, independent community amputation (ability to walk for four minutes without rest or assistive device); 1–3 years post amputation (TTA group); controlled Type-II diabetes (TTA group); no traumatic or cancer-related amputation cause (TTA group); no major amputation on contralateral limb (TTA group); no cardiovascular, orthopaedic, or neurologic wounds, or ulcers that limit physical function; no history of LBP (HC group); no diagnosed rheumatoid arthritis (HC group); no diagnosed osteoarthritis (HC group); and no total hip/knee joint arthroplasty (HC group).

Each participant visited the laboratory for one data collection in which whole body kinematics and core muscle activity were collected during bilateral stepping tasks. Three of the ten TTA participants were unable to perform the tasks bilaterally, and were excluded from the analysis along with the corresponding control of each patient. Each participant provided written, informed consent in accordance with the Colorado Multiple Institutional Review Board.

2.2 Instrumentation and Experimental Protocol

Each participant was instrumented with 63 reflective markers used to obtain whole-body kinematics during step ascent and descent (Gaffney et al. 2016). Marker trajectories were

recorded from eight infrared cameras surrounding the motion capture volume (100 Hz sampling frequency) (Vicon, Centennial, CO).

Core muscle activity was recorded from round bipolar Ag/AgCl surface electrodes (inter-electrode distance: 1cm; CMRR > 100 db) (Vermed, Buffalo, NY) placed on the bilateral lumbar erector spinae (ES), external oblique (OBL), gluteus maximus (GMAX), and gluteus medius (GMED) according to SENIAM guidelines (2000 Hz sampling frequency) (Merletti and Hermens 2000) (Measurement Systems Inc., Livonia, MI). A ground electrode was placed at the C7 vertebrae. Prior to electrode placement, the skin was prepared by shaving and lightly abrading using sterilizing alcohol wipes. Maximum voluntary contractions (MVCs) for these muscles were measured across three trials for approximately three seconds each. For ES MVCs, each participant laid prone and were instructed to extend their trunk while resisting a downward force applied at the shoulders. For OBL MVCs, each participant was seated and instructed to rotate their trunk while resisting a force opposite the direction of the axial rotation applied at the ipsilateral shoulder of the OBL of interest. For GMAX MVCs, each participant laid prone and were instructed to extend their hip while resisting a downward force applied above the knee. For GMED MVCs, each participant laid side-lying and were instructed to abduct their hip while resisting a downward force applied above the knee.

Each participant performed three step ascent and descent trials with each limb onto a 20-cm platform. Each participant instructed to begin the task from a standstill, ascend/descend by leading with the limb instructed, and complete the task in a bilateral standstill. The TTA group was instructed to first perform the task leading with the limb that was most commonly taught in movement retraining (ascent: leading with intact limb; descent: leading with amputated limb), and then was instructed to perform the task leading with the contralateral limb. The HC group was first instructed to perform the task leading with the dominant limb (right limb for all participants), and then instructed to perform the task leading with the non-dominant limb. To limit the potential confounding effect of assistive device use across groups, handrail use was not provided during the ascent/descent tasks. No instructions were provided regarding the speed at which to complete each task.

2.3 Data Analysis

Trunk movements were quantified using RAM and muscle demand was quantified using surface EMG measured from the four bilateral core muscles. Kinematic data were low-pass filtered with a 4th-order Butterworth filter (6 Hz cutoff frequency). A 15-segment subject-specific model was created in Visual 3D and used for analysis (C-Motion, Inc., Germantown, MD).

Trunk RAM is described as:

$$\mathbf{h}_{\text{Trunk}} = \mathbf{I}_{\text{Trunk}} \cdot \boldsymbol{\omega}_{\text{Trunk}} \quad (1)$$

where $\mathbf{I}_{\text{Trunk}}$ and $\boldsymbol{\omega}_{\text{Trunk}}$ are the inertial tensor and angular velocity of the trunk, respectively. To facilitate anatomically planar analyses, all momenta vectors were expressed in a basis with respect to the path of the body COM (Figure 1).

EMG data were band-pass filtered with a 4th-order Butterworth filter (10–350 Hz cutoff frequencies) and smoothed to create a linear envelope using full-wave rectification and a 4th-order zero phase-lag Butterworth filter (6 Hz cutoff frequency). To reduce variability across participants of muscle activation, EMG signals were normalized by the maximum value obtained across the three MVC trials of the respective muscle.

All dependent variables were calculated and normalized to the loading period (leading limb foot strike (0%) to trailing limb foot strike (100%)). Within the loading period, the functional phases of the step ascent and descent were based on the sub-phases previously defined by Zachazewski et al., (1993) (Figure 2).

Muscle demand was quantified by integrating the normalized EMG data during each functional phase:

$$i\text{EMG}_{\text{muscle}} = \int_{t_0}^{t_f} n\text{EMG}_{\text{muscle}} dt \quad (2)$$

where $n\text{EMG}_{\text{muscle}}$ is the linear envelope EMG signal normalized to the maximum linear envelope of the MVC of the respective muscle, and t_0 and t_f are the integrating bounds of $i\text{EMG}$.

2.4 Statistical Analysis

Patient demographics (age and BMI) were compared across groups using two-tailed independent t -tests ($\alpha = 0.05$). Trunk RAM and $i\text{EMG}$ data were averaged across the three trials for both the ascent and descent trials for each participant and used for comparison. Task completion times were compared across groups (leading with the amputated limb vs. HC and leading with the intact limb vs. HC) using two-tailed independent t -tests ($\alpha = 0.05$).

To quantify trunk movements, we identified the peak (minimum and maximum) trunk RAM in all three planes. To quantify the demand from core muscles used to support trunk movement, we calculated $i\text{EMG}$ of each muscle. Each dependent variable (peak RAM and $i\text{EMG}$) was calculated within each functional phase of the step ascent and descent trials. Dependent variables were compared using three one-way ANOVAs: *between* subjects (leading with amputated limb vs. HC and leading with intact limb ascent vs. HC) and *within* subjects (leading with amputated vs. leading with intact limb ascent) while accounting for differences in age, height, and mass across groups in momenta comparisons (covariates). When a significant main or interaction effect occurred, pairwise comparisons with a Bonferroni adjustment for multiple comparisons were used to determine significance ($\alpha_B = 0.05/3 = 0.017$). For the HC group, only trials performed on the right limb were used for statistical comparison. To quantify the change between dependent variables, Hedges' g effect size and bootstrapped 95% confidence intervals were calculated (Hentschke and

Stuttgen 2011) and categorized as small ($g \leq 0.2$), medium ($0.2 < g < 0.8$), and large effect ($g \geq 0.8$).

3. Results

3.1 Patient Demographics

The TTA group was significantly younger than the HC group ($P < 0.01$). No differences in BMI existed across groups (Table 1).

3.2 Task Completion Time

No differences in task completion time existed between the TTA and HC groups or between limbs in the TTA group during step ascent or step descent (Figure 3).

3.3 Step Ascent

3.3.1 Trunk Rotational Angular Momentum (RAM)—In the frontal plane, during vertical thrust phase of step ascent, the peak trunk RAM away from the leading stance foot (negative) was larger in the TTA group when leading with the intact limb than HC ($P = 0.017$, $g = 1.84$ [1.34 4.24]) (Figure 4). During forward continuance, the peak trunk RAM away from the stance foot was greater in the TTA group when stepping onto the amputated limb than HC ($P = 0.01$, $g = 2.51$ [1.41 4.87]) (Figure 4).

In the transverse plane, during weight acceptance, the peak trunk RAM toward the leading stance foot (negative) was greater in the TTA group when leading with both the amputated and intact limbs than HC ($P < 0.01$, $g = 1.85$ [1.05 4.18]; $P = 0.017$, $g = 1.96$ [1.49 3.88], respectively) (Figure 4). During vertical thrust, the peak trunk RAM toward the leading stance foot (negative) was greater in the TTA group when leading with both the amputated and intact limb ($P < 0.01$, $g = 3.02$ [2.10 5.94]; $P < 0.01$, $g = 2.59$ [2.22 4.83], respectively) and the peak trunk RAM away from the leading stance foot (positive) was greater in the TTA group when leading with the intact limb than HC ($P = 0.01$, $g = 1.78$ [1.08 5.16]) (Figure 4).

3.3.2 Integrated EMG (iEMG)—During the weight acceptance phase, the iEMG from the ES on the leading limb side was larger in the TTA group when leading with the intact limb than HC. During the vertical thrust phase, the iEMG from the ES and OBL on the leading and trailing limb sides were larger in the TTA group when leading with both the amputated or intact limb than HC. During the forward continuance phase, the iEMG from the ES and OBL on the leading and trailing limb sides, as well as from the GMAX on the trailing limb side, was larger in the TTA group when leading with both the amputated or intact limb than HC (Figure 5, Table 2).

3.4 Step Descent

3.4.1 Trunk Rotational Angular Momentum (RAM)—In the sagittal plane, during the weight acceptance phase of step descent, the peak posterior trunk RAM was larger in the TTA group when leading with the intact limb than HC ($P < 0.01$, $g = 2.60$ [2.03 4.52]) (Figure 6).

In the frontal plane, during the weight acceptance phase, the peak trunk RAM away from the leading stance foot (negative) was larger in the TTA group when leading with the intact limb than HC ($P < 0.01$, $g = 1.03$ [0.11 2.62]) (Figure 6).

In the transverse plane, during the weight acceptance phase, the peak trunk RAM toward the leading limb (negative) was larger in the TTA group when leading with the intact limb than HC ($P = 0.01$; $g = 1.59$ [0.65 4.45]) (Figure 6).

3.4.2 Integrated EMG (iEMG)—When measured across the entire loading period, the iEMG from the OBL on the leading limb side was larger in the TTA group when leading with the intact limb than HC. During the controlled lowering phase, the iEMG from the ES on the trailing limb side was larger in the TTA group when leading with both the amputated or intact limb than HC. During the controlled lowering phase, the iEMG from the OBL on the trailing limb side was larger in the TTA group when leading with the amputated limb than HC, and the iEMG from the GMAX on the trailing limb side was larger in the TTA group when leading with the intact limb than HC (Figure 7, Table 3).

4. Discussion

The purpose of this study was to identify muscle demand from core trunk/pelvis muscles (bilateral erector spinae (ES), external oblique (OBL), gluteus maximus (GMAX), and gluteus medius (GMED)) associated with trunk movements during step ambulation in people with unilateral transtibial amputation (TTA). Despite the asymmetric trunk movements adopted by patients with TTA during both step ascent and descent compared to healthy controls (HC), there was an increase in bilateral core muscle demand. These results indicate that regardless of an asymmetric trunk movement compensation, the TTA group demonstrated high bilateral core muscle demand during step ambulation, which has potential implications related to development of LBP (Kulkarni et al. 2005; Morgenroth et al. 2010). Because people with TTA are often required to alternate the lead limb when navigating stairs during community ambulation, they would benefit from interventions that step task completion, but without the increased demand placed on the core musculature.

4.1 Step Ascent

When leading with the intact limb, the TTA group adopted a ‘hip dominant strategy’, which may compensate for limited active push-off force from the trailing amputated limb. This strategy corresponded to larger GMAX muscle demand on the leading limb side than the HC group. This observation is similar, but more exaggerated, than the hip-extensor dominant strategy that typically occurs in level-ground amputee gait to assist with forward progression (Fey et al. 2010). Linked to the hip-extensor dominant strategy, the TTA group generated a larger amount of anterior trunk RAM than the HC group to elevate the body COM during weight acceptance, which corresponded with the larger demand from the bilateral ES and OBL muscles. However, there was no difference in timing of demand across the functional phases of ascent between the ES and OBL muscles, which are located posteriorly and anteriorly to the trunk, respectively. We expect that this finding is indicative of the individual strategies adopted by patients with TTA during step ascent.

The TTA group demonstrated greater muscle activity from the trunk lateral bend and rotator muscles (ES and OBL) than the HC group throughout the entire ascent. This strategy adopted during the high-demand task was likely adopted to maintain balance throughout the loading period due to the larger generation of RAM generated by the TTA group in the frontal and transverse planes, which is consistent with a compensated Trendelenburg pattern (Gaffney et al. 2016). This strategy is a common characteristic of amputee gait that results in larger frontal plane trunk displacement toward the limb that is being loaded, and aids in lateral balance by shifting the body COM closer to the base of support (Hof 2008). In addition, this compensation may also relate to 'hip hiking', where the person elevates the pelvis on the swing limb (trailing limb) side to avoid contact between the swing limb and the step, which was accomplished by increased demand from the GMED on the trailing limb side (Nadeau et al., 2003; Gottschall et al., 2012). It is likely that these two compensations are not independent from one another, but simultaneously adopted to assist in task completion.

The TTA group adopted asymmetric trunk movements during step ascent that did not correspond to asymmetric muscle demand. This may indicate limb-dependent motor control compensations that are dependent upon the leading limb. When ascending onto the intact limb, which is what is taught in movement retraining, the TTA group adopted different movements than the HC group that corresponded with high muscle demand throughout the loading period. By contrast, when ascending onto the amputated limb, the TTA group did not adopt a different movement strategy early in the loading period than the HC group, yet had larger demand from the core muscles than the HC group. This finding could be attributed to the limited training of the task for participants who habitually lead step ups with the intact limb. It is well-known that motor control strategies change with training (Thoroughman and Shadmehr, 1999; Lay et al., 2002). Future work should investigate how core muscle demand in patients with TTA is changed during high-demand tasks with continued movement retraining.

4.2 Step Descent

When descending onto the intact limb, the TTA group had reduced ability to actively lower the body COM with the amputated limb. As a result, the TTA group 'falls' into the intact limb, which we identified with larger RAM generation during loading compared to the HC group. In preparation for the increased loading, the TTA group adopted a trunk stiffening compensation to prevent collapse in the presence of larger RAM and maintain balance by limiting perturbations to the body COM, which that resulted in large core muscle demand. This protective strategy may be used to prevent additional injury surrounding the spine (Solomonow et al. 2008).

In general, this cohort of people with TTA self-reported that step descent onto the intact limb was the hardest task to complete, which may have induced fear or anxiety while performing this task. This is similar to a previous investigation describing the anxiety of people descending steps with an ankle foot orthosis (Nahorniak et al. 1999). While lack of ankle control with a passive prosthesis limits controlled lowering, core muscle training may help

improve self confidence in preparation for the increased loads that are associated with stepping onto the intact limb.

When stepping onto the amputated limb, the TTA group adopted a similar trunk stiffening by increasing the demand of core trunk/pelvis musculature, yet this did not coincide with asymmetric movement patterns. To maintain balance when descending onto the amputated limb, the TTA group limited the perturbations of the body COM by limiting the amount of generation of trunk RAM, which increased bilateral core muscle demand. This strategy is consistent with other conservative strategies adopted by people with TTA to prevent falls when loading the amputated limb during high-demand tasks such as walking on uneven surfaces (Paysant et al. 2006), stairs (Ramstrand and Nilsson 2009), or inclined surfaces (Vickers et al. 2008). Although people with TTA may have greater confidence performing the task by increasing muscle demand to account for balance deficits, increased and repetitive guarding strategies may become consequential over time through the development of LBP or other overuse injuries (Kumar 2001; McGill 2007).

4.3 Clinical Application

Based on our results, we recommend that movement retraining for people with TTA include step ambulation leading with either limb, which can likely be accomplished through targeted training of core trunk muscles (Kahle and Tevald 2012). Without the function of the ankle and reduced lever arm of the knee extensors, movement compensations are necessary. Based on our results, the similarity of trunk RAM across patients may indicate that the trunk is the segment that drives the motion, and that the pelvis compensates. However, with training and familiarity, the unnecessary core muscle demand could be reduced, and may provide more efficient postural control resulting in a reduced risk of falling when navigating an unexpected obstacle (Marigold et al. 2005; Molina-Rueda et al. 2015).

Establishing the association between muscle demand and movements identified through RAM, which is based on angular velocity, has clinical implications as wearable sensors (e.g. gyroscopes) become more feasible for clinical use (Watanabe et al. 2011). Future work should focus on identifying specific associations between movements and muscle demand, and using them to improve rehabilitation for optimizing movement patterns following lower limb amputation.

4.4 Limitations

There are several limitations to consider with this investigation. First, there was a wide variability of step completion time among people with TTA, which has been shown to be correlated with muscle demand (Larsen et al. 2008). Second, the TTA group was not screened for LBP at the time of testing; therefore, we cannot conclude if the movements adopted were habitual patterns or a result of LBP. However, we do not anticipate this to have a confounding effect on our results because no TTA group participant reported LBP at the time of testing. When asked “Did you experience any pain during that exercise?” following a maximum isometric contraction of the low back muscles, which can induce pain in patients with chronic LBP (Kankaanpää et al. 1998), all participants self-reported no pain. Third, there was a significant difference in age between the TTA and HC groups, which is known to

have an effect on muscle activation (Frontera et al. 2000; Laughton et al. 2003). However, because age was included as a covariate in all analyses, we do not expect this to have a confounding effect on our findings. Fourth, our findings are likely not only attributed to the amputation itself. Given the additional comorbidities that are likely present in the TTA group, we expect that movement patterns are adopted due to the general poor physical health. Finally, this investigation included a small homogenous dysvascular TTA sample, which may limit the generalizability of these results to people with unilateral TTA from causes other than neurovascular disease.

5. Conclusion

To our knowledge, these results are the first to demonstrate the high demand of core muscles in people with TTA needed to support trunk movements during step ascent and descent. Regardless of the leading limb, the TTA group increased demand from the core muscles during both step ascent and descent. Asymmetric trunk movements did not correspond to asymmetric core muscle demand, which has potential clinical implications related to targeting research and clinical interventions to improve movement symmetry and prevent secondary pain conditions, such as LBP.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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	<u>Sagittal Plane</u>	<u>Frontal Plane</u>	<u>Transverse Plane</u>

Positive Rotation	<i>Posterior</i> rotation with respect to the stance foot	Mediolateral rotation toward the stance foot	Axial rotation away from the stance foot
Negative Rotation	<i>Anterior</i> rotation with respect to the stance foot	Mediolateral rotation away from the stance foot	Axial rotation toward from the stance foot

Figure 1. All momenta vectors were expressed in a path reference frame that is defined by the path of the body COM ($e_{sagittal}$, $e_{frontal}$, $e_{transverse}$).

Figure 2. Functional phases of the (a) step ascent and (b) step descent tasks expressed as a percentage of the loading period (leading limb foot strike to trailing limb foot strike) (Zachazewski et al. 1993).

Figure 3.

Mean (1 SD) step ascent and descent completion times (leading limb foot strike to trailing limb foot strike) for the transtibial amputation (TTA) and healthy control (HC) groups.

Figure 4.

Ensemble averages of trunk rotational angular momentum (RAM) during the *step ascent*. Statistically significant differences ($P < 0.017$) within and across groups are: amputated vs. intact limbs ($\blacktriangle$), amputated limb vs. healthy controls (*), and intact limb vs. healthy controls (+).

Figure 5.

Ensemble averages of normalized linear envelope and integrated EMG (iEMG) of (a) leading limb side and (b) trailing limb side muscles during the phases of the *step ascent*: weight acceptance (WA), vertical thrust (VT), and forward continuance (FC). See Section 2.2 for specific muscle acronym definitions. Statistically significant differences ($P < 0.017$) within and across groups are: amputated vs. intact limbs (▲), amputated limb vs. healthy controls (*), and intact limb vs. healthy controls (+).

Figure 6.

Ensemble averages of trunk rotational angular momentum (RAM) during the *step descent*. Statistically significant differences ($P < 0.017$) within and across groups are: amputated vs. intact limbs ($\blacktriangle$), amputated limb vs. healthy controls (*), and intact limb vs. healthy controls (+).

Figure 7.

Ensemble averages of normalized linear envelope and integrated EMG (iEMG) of (a) leading limb side and (b) trailing limb side muscles during the phases of the *step descent*: weight acceptance (WA), forward continuance (FC), and controlled lowering (CL). See Section 2.2 for specific muscle acronym definitions. Statistically significant differences ($P < 0.017$) within and across groups are: amputated vs. intact limbs (▲), amputated limb vs. healthy controls (*), and intact limb vs. healthy controls (+).

Table 1

Participant characteristics for patients with dysvascular unilateral transtibial amputation (TTA) and healthy control (HC) groups.

Group	Age (Years)	BMI (kg/m ²)	Time since Amputation (Months)	Residual Limb Length (cm)	Socket Type	Prosthetic Foot
TTA	56.3 ± 4.5 [*]	28.3 ± 2.7	16.7 ± 5.2	14.4 ± 2.9	Total contact carbon fiber	Dynamic elastic response
HC	64.6 ± 5.5 [*]	27.4 ± 3.3	N/A	--	--	--

^{*} Indicates significant difference in age across groups ($P < 0.05$).

Table 2

Statistical comparisons across groups (intact limb vs. healthy control and amputated limb vs healthy control) and across limbs (amputated vs. intact limbs) during the functional phases of the *step ascent*. See Section 2.2 for specific muscle acronym definitions. Statistically significant differences following Bonferroni correction ($P < 0.017$) of pairwise comparisons are noted as: intact limb vs. healthy controls (+), amputated limb vs. healthy controls (*), and amputated vs. intact limbs (▲).

	<i>Muscle</i>	<i>Weight Acceptance</i>		<i>Vertical Thrust</i>		<i>Forward Continuation</i>	
		<i>P-value</i>	<i>Hedge's g</i>	<i>P-value</i>	<i>Hedge's g</i>	<i>P-value</i>	<i>Hedge's g</i>
<i>Intact Limb vs. Healthy Control</i>	Leading Limb Side ES	0.03+	1.87 [1.12 4.43]	<<0.01+	2.68 [2.04 5.16]	<0.01+	1.80 [1.40 6.26]
	Leading Limb Side OBL	0.06	1.88 [1.24 3.89]	0.03+	1.62 [1.05 3.30]	0.01+	2.02 [1.37 4.49]
	Leading Limb Side GMAX	0.83	0.55 [-0.19 1.58]	0.33	1.14 [0.60 2.63]	0.61	0.82 [0.54 1.62]
	Leading Limb Side GMED	0.82	0.64 [-0.07 1.71]	0.26	0.77 [0.21 1.69]	0.54	0.82 [0.54 1.62]
	Trailing Limb Side ES	0.24	1.39 [0.69 2.95]	<<0.01+	3.60 [2.55 8.22]	<<0.01+	4.82 [3.79 8.63]
	Trailing Limb Side OBL	0.17	1.44 [0.81 2.93]	0.1	1.49 [0.80 3.04]	<0.01+	1.79 [1.35 3.31]
	Trailing Limb Side GMAX	0.10	1.46 [0.82 4.49]	0.03+	1.93 [1.02 5.95]	0.11	0.015 [-1.41 0.57]
	Trailing Limb Side GMED	0.52	0.74 [-0.16 1.73]	0.07	1.00 [0.36 2.23]	0.57	0.55 [-0.40 1.56]
<i>Amputated Limb vs. Healthy Control</i>	Leading Limb Side ES	0.16	1.05 [0.49 2.33]	<0.01*	2.12 [1.50 4.24]	<0.01*	2.81 [1.67 6.73]
	Leading Limb Side OBL	0.30	0.76 [0.49 2.60]	0.21	0.98 [0.71 2.83]	<0.01*	1.81 [1.17 4.06]
	Leading Limb Side GMAX	0.96	0.07 [-1.02 1.49]	0.48	0.97 [0.26 2.01]	0.20	1.27 [0.87 2.29]
	Leading Limb Side GMED	0.93	0.25 [-0.68 1.76]	0.60	0.02 [-0.67 0.84]	0.20	0.44 [-0.06 1.45]
	Trailing Limb Side ES	0.49	0.47 [-0.83 1.53]	0.01*	2.30 [1.78 4.33]	0.01*	2.32 [1.75 4.70]
	Trailing Limb Side OBL	0.03	1.34 [0.83 2.58]	0.01*	1.78 [1.21 3.47]	0.01*	2.41 [1.94 4.81]
	Trailing Limb Side GMAX	0.43	1.00 [0.59 2.21]	0.26	1.32 [0.74 2.63]	0.02	1.39 [0.57 4.01]
	Trailing Limb Side GMED	0.15	0.89 [0.60 1.61]	0.04	1.67 [1.02 3.51]	0.20	1.01 [2.82 2.33]
<i>Amputated vs. Intact Limbs</i>	Leading Limb Side ES	0.14	0.79 [-0.07 2.16]	0.53	0.32 [-0.62 1.39]	0.23	0.62 [-0.26 3.64]
	Leading Limb Side OBL	0.21	0.66 [-0.06 2.37]	0.47	0.37 [-0.16 1.63]	0.26	0.59 [-0.03 1.69]
	Leading Limb Side GMAX	0.25	0.61 [0.06 1.92]	0.58	0.28 [-0.31 1.25]	0.28	0.56 [0.09 1.30]
	Leading Limb Side GMED	0.14	0.79 [-0.20 2.55]	0.19	0.70 [0.35 1.53]	0.60	0.27 [-0.48 0.80]
	Trailing Limb Side ES	0.23	0.63 [0.12 2.00]	0.69	0.20 [-0.32 1.28]	0.19	0.74 [-0.12 1.7]
	Trailing Limb Side OBL	0.96	0.03 [-0.84 0.88]	0.37	0.47 [-0.38 1.79]	0.13	0.81 [0.04 1.95]
	Trailing Limb Side GMAX	0.72	0.19 [-1.28 1.15]	0.72	0.19 [-0.84 1.30]	0.52	0.33 [-0.70 1.78]

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	Muscle		Weight Acceptance		Vertical Thrust		Forward Continuanace	
	P-value	Hedge's g	P-value	Hedge's g	P-value	Hedge's g	P-value	Hedge's g
Trailing Limb Side GMED	0.53	0.33 [−0.54 1.53]	0.57	0.29 [−0.39 1.04]	0.67	0.22 [−0.23 1.24]		

Table 3

Statistical comparisons across groups (intact limb vs. healthy control and amputated limb vs healthy control) and across limbs (amputated vs. intact limbs) during the functional phases of the *step descent*. See Section 2.2 for specific muscle acronym definitions. Statistically significant differences following Bonferroni correction ($P < 0.017$) of pairwise comparisons are noted as: intact limb vs. healthy controls (+), amputated limb vs. healthy controls (*), and amputated vs. intact limbs (▲).

	<i>Muscle</i>	<i>Weight Acceptance</i>		<i>Forward Continuation</i>		<i>Controlled Lowering</i>	
		<i>P-value</i>	<i>Hedge's g</i>	<i>P-value</i>	<i>Hedge's g</i>	<i>P-value</i>	<i>Hedge's g</i>
<i>Intact Limb vs. Healthy Control</i>	Leading Limb Side ES	0.24	0.61 [0.04 3.05]	0.25	1.16 [0.36 3.53]	0.02	1.37 [0.93 2.58]
	Leading Limb Side OBL	0.01+	1.52 [0.96 3.02]	0.01+	1.98 [1.27 4.16]	0.01+	1.48 [0.73 3.64]
	Leading Limb Side GMAX	0.116	1.13 [0.59 2.16]	0.15	1.11 [0.60 2.14]	0.20	0.68 [0.16 1.81]
	Leading Limb Side GMED	0.17	1.08 [0.46 2.16]	0.16	0.95 [0.52 1.94]	0.37	0.47 [-0.35 1.26]
	Trailing Limb Side ES	0.08	1.29 [0.57 2.50]	0.05	1.95 [1.23 3.92]	<0.01+	1.82 [0.78 4.17]
	Trailing Limb Side OBL	0.02	0.94 [-0.15 2.82]	0.13	1.16 [1.23 3.92]	0.02	1.33 [0.74 3.16]
	Trailing Limb Side GMAX	0.03	1.16 [0.79 2.31]	0.61	0.83 [0.12 1.85]	0.01+	1.63 [0.96 3.16]
	Trailing Limb Side GMED	0.36	0.96 [0.36 2.20]	0.50	0.51 [-0.49 1.40]	0.12	0.84 [-0.27 2.87]
<i>Amputated Limb vs. Healthy Control</i>	Leading Limb Side ES	0.39	0.34 [-0.70 1.12]	0.40	0.64 [0.03 1.83]	0.09	1.30 [0.38 3.41]
	Leading Limb Side OBL	0.34	0.75 [0.55 2.77]	0.30	0.80 [0.64 3.13]	0.08	0.85 [-0.10 3.93]
	Leading Limb Side GMAX	0.11	1.33 [0.76 3.43]	0.66	0.86 [0.30 2.38]	0.86	0.56 [0.01 1.70]
	Leading Limb Side GMED	0.50	0.55 [-0.51 1.30]	0.71	0.26 [-0.31 1.07]	0.64	0.03 [-0.72 0.80]
	Trailing Limb Side ES	0.52	0.57 [0.23 1.90]	0.17	1.42 [1.07 3.71]	0.02*	2.05 [1.33 4.45]
	Trailing Limb Side OBL	0.52	0.82 [0.18 1.73]	0.09	1.13 [0.72 2.16]	0.02*	1.53 [0.99 3.12]
	Trailing Limb Side GMAX	0.46	0.72 [0.43 2.40]	0.50	0.88 [0.38 2.31]	0.29	1.26 [0.48 5.69]
	Trailing Limb Side GMED	0.70	0.44 [-0.39 1.40]	0.54	0.83 [0.04 1.92]	0.14	0.81 [-0.26 2.32]
<i>Amputated vs. Intact Limbs</i>	Leading Limb Side ES	0.78	0.14 [-0.30 2.34]	0.54	0.32 [-0.15 1.78]	0.55	0.31 [-0.34 0.77]
	Leading Limb Side OBL	0.17	0.73 [0.14 2.00]	0.47	0.38 [-0.43 2.51]	0.20	0.69 [-0.02 1.94]
	Leading Limb Side GMAX	0.83	0.11 [-0.71 0.98]	0.38	0.46 [-0.30 1.33]	0.88	0.08 [-0.45 0.79]
	Leading Limb Side GMED	0.70	0.20 [-0.47 1.92]	0.16	0.78 [0.46 1.51]	0.36	0.48 [-0.01 1.08]
	Trailing Limb Side ES	0.73	0.18 [-1.76 0.75]	0.35	0.50 [-0.23 1.17]	0.17	0.74 [-0.23 2.13]
	Trailing Limb Side OBL	0.99	0.47 [-0.65 1.18]	0.29	0.57 [-0.44 1.57]	0.23	0.63 [-0.22 1.85]
	Trailing Limb Side GMAX	0.33	0.51 [-0.13 1.53]	0.58	0.29 [-0.89 0.94]	0.13	0.85 [0.09 1.88]

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	<i>Weight Acceptance</i>		<i>Forward Continuation</i>		<i>Controlled Lowering</i>	
	<i>P-value</i>	<i>Hedge's g</i>	<i>P-value</i>	<i>Hedge's g</i>	<i>P-value</i>	<i>Hedge's g</i>
<i>Muscle</i>						
Trailing Limb Side	0.25	0.62 [0.10 1.57]	0.45	0.40 [-1.23 1.01]	0.73	0.18 [-0.58 1.08]