The Associations between Asymmetries in Quadriceps Strength and Gait in Unilateral Transtibial Amputees

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Abstract

Background – Individuals with unilateral transtibial amputations (ITTAs) are asymmetrical in quadriceps strength. It is unknown if this is associated with gait performance characteristics such as walking speed and limb symmetry.

Research Question – Are quadriceps strength asymmetries related to walking speed and/ or gait asymmetries in ITTAs?

Methods – Knee-extensor isometric maximum voluntary torque (MVT) and rate of torque development (RTD) were measured in eight ITTAs. Gait data were captured as the ITTAs walked at self-selected habitual and fast speeds. Step length and single support time, peak knee extension moments and their impulse and peak vertical ground reaction force (vGRF) in the braking and propulsive phases of stance were extracted. Bilateral Asymmetry Index (BAI) and, for gait variables only, difference in BAI between walking speeds (ΔBAI) were calculated. Correlation analyses assessed the relationships between MVT and RTD asymmetry and (1) walking speed; (2) gait asymmetries.

Results – Associations between strength and gait BAIs generally became more apparent at faster walking speeds, and when the difference in BAI between fast and habitual walking speed was considered. BAI RTD was strongly negatively correlated with habitual and fast walking speeds (r=~0.83). Larger BAI RTD was strongly correlated with propulsive vGRF BAI in fast walking, and larger ΔBAIs in vGRF during both the braking and propulsion phases of gait (r=0.74–0.92). ITTAs who exhibited greater BAI MVT showed greater ΔBAI in single support time (r=0.83).

Significance – While MVT and RTD BAI appear to be associated with gait asymmetries in ITTAs, the magnitude of the asymmetry in RTD appears to be a more sensitive marker of walking speed. Based on these results, it’s possible that strengthening the knee-extensors of the amputated limb to improve both MVT and RTD symmetry may benefit walking speed, and reduce asymmetrical loading in gait.

Key words: maximum voluntary torque, rate of torque development, walking speed, gait mechanics, loading

Introduction

Muscle strength (the ability to produce force) can be measured as the peak/maximum voluntary joint torque (MVT) during isometric maximum voluntary contractions (MVC), or as rate of torque development (RTD) during rapid isometric contractions from low or resting torques [1–3]. While MVT defines the upper limit of a muscle's force production capacity, it takes time (>150 ms) to achieve MVT [4,5] when contracting from rest. Thus, RTD is considered more functionally relevant in human movement, particularly when time to develop torque is limited, such as if restabilising the body following mechanical perturbation, or in sporting activities [6–9]. Individuals with unilateral transtibial amputations (ITTAs), characterised by musculoskeletal asymmetry stemming from the loss of an ankle joint on one side, display reduced quadriceps MVT of 41–60% [10–14], and RTD of 75% [14] in the amputated limb compared to the intact. It is important to understand the functional implications of such strength asymmetries, if any, as this may inform exercise and rehabilitation programmes to improve function.

Walking speed, an important indicator of functional gait capacity [15], is lower in ITTAs than able-bodied populations (1.25 m/s vs. ~1.4 m/s; [16–18]), and previous research has identified a need to investigate the factors underlying these changes in gait speed characteristics [17]. ITTAs also display greater asymmetry during gait than able-bodied individuals (e.g. reduced amputated limb stance time [19,20], peak vertical ground reaction force (vGRF) [19], and contralateral step length [21]), which may predispose them to degenerative co-morbidities [22–24]. Whilst the mechanisms are likely multifaceted, it is possible that knee-extensor strength asymmetries may be a contributing factor to the slower walking speeds and asymmetrical gait apparent in ITTAs, given the role of the quadriceps in dynamic shock absorption in early stance [25]. Specifically, ITTAs with larger quadriceps strength asymmetries (and thus, reduced capacity to absorb loads on the amputated side) may select slower walking speeds and favour loading their intact limb, to minimise loads on the amputated side. This would also be consistent with the reduced knee flexion angles and lower knee-extensor moments and powers (particularly the K1 and K2 phases) observed in the amputated, relative to the intact, limb during walking [18,26–28]. Amputated limb disuse resulting from loading asymmetry may further contribute to strength asymmetry [14], compounding walking gait asymmetry. While knee-extensor MVT asymmetry doesn't appear associated with self-selected walking speeds [29], there is evidence that it may be related to aspects of gait asymmetry [13,29]. Given RTD is more closely associated with functional capacity than MVT in older adults and injured athletes [30–33], it's possible knee-extensor RTD asymmetry may be more closely associated with walking speed and gait asymmetry in ITTAs.

Previous investigations of associations between strength asymmetry and walking speed and/or gait asymmetry in ITTAs have considered habitual speeds [13,29]. However, the capacity to walk at faster speeds is useful for completing several mobility-dependent tasks of daily living [34] as well as improving/maintaining cardiovascular fitness. As speed increases, increased lower-limb muscular force is required to absorb and generate impact forces. In ITTAs, much of this additional demand is met by the intact limb [27]. It is therefore conceivable that strength asymmetries may: (1) become more closely associated with speed and gait asymmetries during fast walking; (2) limit the range of speeds an ITTA is able to walk at (measured as the difference between fast and habitual walking speed); and (3) relate to any increase in gait asymmetries when walking at fast, compared to habitual speeds (measured as the difference in asymmetry between fast and habitual speed).

This study investigated the associations of ITTA knee-extensor MVT and RTD asymmetry, with both self-selected walking speed and gait asymmetry (kinetic and temporospatial) during habitual and fast walking.

Methods

Eight male ITTAs provided informed written consent (Table 1). Ethical approval was obtained from the University of Roehampton's Ethics Committee (LSC 16/176) and the NHS Health Research Authority (17/NW/0566).

**TABLE 1*

To ensure established ambulation, only individuals with a primary unilateral transtibial amputation >6 months prior to involvement in the study, and a minimum functional K3 rating [35], were recruited. Further exclusion criteria included pain/discomfort in the residual limb whilst using their prosthesis; amputation due to complications arising from metabolic conditions (e.g., diabetes); residuum shorter than 10 cm; and cardiovascular disease risk factors or neuro-musculoskeletal injuries (other than a transtibial amputation). All ITTAs wore feet classified as passive energy storage and return.

Experimental Setup

Participants visited the laboratory on three separate occasions (3-7 days between each visit) to complete familiarisation of the strength measurements (visit 1), strength measurements (visit 2), and biomechanical measurements during walking (visit 3). A familiarisation session was used to improve the reliability of strength measures [36], whilst strength and gait analyses occurred on separate days to avoid fatiguing effects of one on the other. Sessions commenced at a consistent time of day (± 2 hours) for each participant, following at least 36 hours without strenuous exercise, and 24 hours without alcohol.

Strength Data Collection

Isometric strength data were collected with the prosthesis removed using an isokinetic dynamometer (Humac Norm, Computer Sports Medicine Inc., Massachusetts, USA). Participants were seated with a hip angle of 80° flexion from the vertical line, the knee at ~70° flexion during near-maximal isometric extension, and tightly strapped across the pelvis and shoulders. Basic modifications were made to the chair to minimise knee angle changes during contractions, including the use of a dense foam padding on the seat and limb attachment, and a custom-made lower-limb attachment tightly clamped to the crank-arm to prevent extraneous rotation. This was placed as distal on the tibia as anatomy and participant comfort permitted. For the amputated limb, the crank arm was rotated by 180° from its standard position for testing seated knee-extension strength, to account for the shorter residual tibia (Supplementary Material, Figure S1).

Analogue torque signals were sampled at 2000 Hz using an external A/D converter (16-bit signal recording resolution; Micro 1401, CED, Cambridge, UK) and Spike 2 software (version 8; CED), and filtered off-line, using a low-pass fourth-order Butterworth filter with a 10-Hz cut-off. Limb weighting was conducted with the participant sat rested for at least two seconds in the dynamometer, with no discernible change in mean of baseline torque or quadriceps muscles EMG signals (note, EMG were collected as described previously [14], but not used for measurements in this study). This baseline torque was subtracted from all active torque recordings to correct for the weight of the limb.

Strength measurements were performed on both limbs, with start limb randomised. Following a warm-up (20 warm-up contractions at progressively higher intensities), participants completed three maximum voluntary contractions (MVCs). Each was separated by 30-45 s, and involved participants pushing 'as hard as possible' for 3-5 s. Torque output was displayed on a computer monitor in front of the participant. MVT was the greatest instantaneous torque recorded during any of the MVCs or explosive contractions (see below).

Participants then completed 10-15 explosive contractions of the knee-extensors, each separated by 20 s rest. Participants were instructed to extend their knee 'as fast and hard as possible' for 1 s, with emphasis on 'fast', aiming to achieve >80% MVT as quickly as possible. The maximum slope of the torque-time curve (peak voluntary RTD; calculated as ΔTorque/ΔTime over a 25-ms moving time window) of each contraction was displayed on the monitor. Resting baseline was also displayed, providing biofeedback on whether any countermovement or pretension occurred before the contraction. Peak RTD was averaged across the three explosive contractions with the highest peak RTD which demonstrated peak torque >80% MVT, and no discernible countermovement or pre-tension (quantified as change of baseline torque <0.5 Nm during the 100 ms prior to visible torque onset) [37]. MVT and RTD are presented as absolute (Nm and $Nm.s^{-1}$) and relative to body mass (MVT_{BM}, $Nm.kg^{-1}$; and RTD_{BM}, $Nm.s^{-1}.kg^{-1}$; respectively).

Biomechanical Data Collection

Kinematic data were collected using twelve Vicon Vantage V5 (Vicon Motion Systems Ltd.; Oxford, UK) motion capture cameras sampling at 200 Hz, synchronised with three in-series force plates recording at 1000 Hz (Type 9281c; Kistler Instruments Ltd., Hampshire, UK) placed in the middle of a 15-m walkway. Two sets of Brower TC timing gates (Brower Timing, Utah, USA) placed 2-m either side of the force plates captured average walking pace.

Retroreflective markers (14 mm diameter) were attached according to the Plug-In-Gait lower-body marker set [38]. Markers for the shank, ankle and foot were placed in positions on the prosthetic corresponding to those on the intact limb [39,40].

Following three preliminary trials, during which average self-selected habitual walking speed was determined, participants were instructed to walk along the walkway until five ‘good’ trials (a single pass along the walkway in one direction, within ±5% of average walking speed and a successful force plate strike) had been collected for each limb. This protocol was repeated for a self-selected fast walking speed (a pace participants would choose if running late for an appointment). The three trials closest to average walking speed were selected for analysis for each speed. Data processing, including inverse dynamics calculations, of gait parameters was completed using Nexus (version 2.7.1, Vicon, Oxford).

The anthropometric characteristics of all participants were based on Dempster’s values [41]. In ITTAs, the inverse dynamic analysis assumes that the prosthetic components were anatomically equivalent to the intact limb. A low-pass zero-lag fourth-order Butterworth filter was used to filter raw marker trajectories (8 Hz) and analogue force data (200 Hz cut-off).Walking speed and single support time were extracted using custom-developed code (Matlab R2016a, The Mathworks Inc, Natick, MA). The difference in speed between habitual and fast (ΔSpeed; used as an indicator of the range of speeds the participant is able to walk at) was calculated as

$$\Delta\text{Speed} = \text{Walking Speed}_{Fast} - \text{Walking Speed}_{Habitual} \tag{1}$$

Kinetic parameters extracted were peak vGRF during the braking and propulsive phases of stance, and, in braking only, peak internal knee-extensor moment and moment-impulse. Data were normalised to each participant's body mass. Knee-extension moment-impulse was calculated as the cumulative time-integral of the knee-extensor moment. Braking (~0–50%) and propulsion (~50–100%) phases of stance were determined using the antero-posterior ground reaction forces (hGRF) – the first instance of positive hGRF indicating the end of the braking phase.

Asymmetry Calculation

Bilateral Asymmetry Index (BAI) is preferable to some other equations (e.g. Bilateral Strength Asymmetry [14,42] or Limb Symmetry Index [43,44]) for the quantification of asymmetry in a bilateral task, as differences in force between limbs are always relative to the sum force value; thus, the influence of the contralateral limb is accounted for.

BAI [45] was generated for each variable of interest (x) using the formula

$$\text{BAI}x(\%) = \frac{(Intact_x - Amputated_x)}{(Intact_x + Ampuated_x)} \times 100 \tag{2}$$

resulting in a negative value if a greater value was recorded on the amputated limb (BAI=0 indicates perfect symmetry). BAI for absolute and relative data is identical as body mass is included both in fraction and numerator.

The difference in BAI (ΔBAI) for a given variable in gait between habitual and fast walking speeds was calculated as

$$\Delta \mathrm{BAIx} = \mathrm{BAI\_Fast}_x - \mathrm{BAI\_Habit}_x \tag{3}$$

where BAI_Fast and BAI_Habit are the BAI for a given variable (x) at fast and habitual speeds, respectively. ΔBAI for each variable in gait was determined to assess the individual changes in BAI that may occur between habitual and fast walking speeds.

Statistical Analysis

Levene's test checked for equality of variances. Paired *t*-tests compared each strength and gait variable between the intact and amputated limb. Effect size (Hedges g) was calculated for all comparisons, and interpreted as small (g=0.2–0.5), medium (g=0.5–0.8) and large effects (g>0.8) [46]. Where variables were greater in the amputated than intact limb, g was negative.

To determine the relationships between both aspects of strength asymmetry and gait variables, Pearson's product-moment correlations were performed between BAI MVT and, separately, BAI RTD; with (1) habitual and (2) fast walking speeds; (3) ΔSpeed; (4) each gait variable BAI; and (5) ΔBAI. To ensure the correlations in (4) were independent of self-selected walking speed, the criteria outlined in Table 2 were used to select the type of correlation (i.e. bivariate, semi-partial, or partial). Relationships were interpreted as strong (r>0.7), moderate (r=0.5–0.7), or weak (r=0.3–0.5) [47].

BAIs were reported as mean±SD. Statistical analysis was completed using SPSS v24. The significance level for paired t-tests was set at $p<0.05$. Significance level for multiple correlations of the same strength BAI variable with a walking gait parameter was corrected using Benjamini-Hochberg procedure. Briefly, individual *p*-values from correlational analyses were ranked from smallest to largest. Benjamini-Hochberg critical values (x) were calculated for each *p*-value using the formula $x = \left(\frac{i}{m}\right) Q$, where i is the individual *p*-value's rank, m is the total number of tests, and Q is the false discovery rate, set at 20% [48,49]. Statistical significance was assumed for all correlational analyses whereby the calculated critical value was less than original *p*-value. Significant correlations following correction are stated in the results.

TABLE 2

Results

Strength and Gait Asymmetries

Significant strength asymmetries were apparent: both MVT (p=0.003, g=2.01) and RTD (p<0.001, g=2.36) were greater in the intact compared to the amputated limb (Table 3).

TABLE 3

Self-selected fast walking speeds were significantly greater than habitual walking speeds (p<0.001, g=1.88; Table 1).

There were significant differences between limbs at both speeds for all gait variables (temporospatial: p≤0.006, g=0.93–1.41; kinetics p≤0.008, g=1.56–3.45; Table 4), except single support time during fast walking *(p*=0.218, g=0.32*).*

TABLE 4

Relationships between Strength Asymmetry and Walking Speed

BAI MVT was not related to habitual or fast walking speeds (r= -0.42 – -0.25, p=0.301–0.548; Figure 1A and C), but there were strong, significant negative relationships between BAI RTD and both habitual and fast walking speeds (r=~0.83, p≤0.012; Figure 1B and D). Moderate negative relationships were observed between ΔSpeed and both BAI MVT and BAI RTD (r=~0.60, p=0.099–0.129; Figure 1E and F).

FIGURE 1

Relationships between Asymmetries in Strength and Gait

At habitual walking speeds, relationships between BAI MVT and RTD and each of the temporospatial parameters of gait were weak to non-existent (r=-0.30–0.45, *p*=0.311–0.858; Table 5). At fast walking speeds, BAI single support time was moderately related to BAI MVT (r=0.60, *p*=0.116). BAI step length was moderately related to BAI RTD (r=0.58, *p*=0.229 Table 5).

****TABLE 5****

There was a strong, positive relationship between ΔBAI single support time and BAI MVT (r=0.83, *p*=0.010), but a weak relationship between ΔBAI step length and BAI MVT (r=0.41, *p*=0.316). Both ΔBAI single support and ΔBAI step length were moderately correlated with BAI RTD (r=~0.60, *p*≤0.123; Table 5).

Moderate negative correlations were apparent between BAI MVT and BAI knee-extensor impulse (r=-0.56, *p*=0.195) at fast walking speeds, and BAI knee-extensor moment and BAI RTD at habitual walking speeds (r=-0.60, *p*=0.132; Table 5).

At both walking speeds, braking and propulsive phase BAI vGRF were not, or only weakly, correlated with BAI MVT (r=-0.42 – -0.01, *p*=0.195–0.994). ΔBAI propulsive phase vGRF was moderately correlated with BAI MVT (r=0.59, *p*=0.126; Table 5). Moderate to strong positive correlations were observed between BAI RTD and BAI vGRF in both braking and propulsion, for fast (r=0.54–0.74, *p*=0.048–0.206), but not habitual (r=0.10–0.35, *p*=0.529–0.994), walking speeds (Table 5). Furthermore, there were strong, significant correlations between BAI RTD and ΔBAI vGRF in both braking (r=0.89, *p*=0.003) and propulsion (r=0.92, *p*=0.001; Table 5).

Discussion

The correlations between RTD asymmetry with walking gait speed and gait asymmetries observed in this study provide novel evidence that ITTAs with large RTD asymmetry walk more slowly, use their amputated limb much less than their intact limb during propulsion in fast walking, and experience greater increases in loading asymmetry when walking at fast vs.

habitual speeds. MVT asymmetry was strongly correlated only with the difference in single support asymmetry (ΔBAI), suggesting that ITTAs with larger MVT asymmetries tend to increase their single support asymmetry when walking at fast compared to habitual speeds.

BAI RTD was strongly negatively related to both habitual and fast walking speeds, and moderately correlated with ΔSpeed (Figure 1). Thus, our results suggest knee-extensor RTD symmetry may be a limiting factor for functional capacity during walking in ITTAs. Evidence from our correlational analysis suggests that slower self-selected walking speeds may be a result of the amputated limb in individuals with larger RTD asymmetry being less able to contribute to absorption and propulsion loads. Asymmetries in RTD were also associated with vertical limb loading asymmetries during walking – the magnitude of which (~10%) was similar to those of earlier studies [18,50] (Table 4). When asked to walk fast, these asymmetries in absorption and propulsion vGRF increased to a greater extent in the ITTAs with larger RTD asymmetry, as shown by the strong relationships between BAI RTD and ∆BAI vGRF (r=~0.9; Table 5). Collectively, these observed correlations suggest that in ITTAs with greater RTD asymmetries, the amputated limb is less able to contribute to braking or propulsion. This may result in both limiting their walking speed, and causing limb loading asymmetry which is exacerbated at faster walking speeds where loading demands are greater. This is an important consideration – particularly in those ITTAs who aim to be more active and need to withstand increases in exercise intensity – if we consider the hypothesised link between loading asymmetry and the high prevalence of degenerative neuromuscular conditions in this population [13,51,52]. Alternatively, these relationships could be due to the need to preserve stability during gait, as previous research has shown positive correlations between RTD and balance performance in healthy, able-bodied adults [9,53]. As faster walking speeds may decrease gait stability in certain populations [54,55] it is conceivable that ITTAs with greater deficits in RTD in the amputated limb select a slower walking speed to ensure stable walking gait.

In common with previous research [29], BAI MVT was not related to habitual nor fast walking speed (Figure 1). However, it was associated with asymmetry in some gait parameters – in particular, single support time. As expected, ITTAs spent longer in single support on the intact when compared to the amputated limb [13]. Although there was an overall decrease in mean BAI single support from habitual to fast walking, individual changes in asymmetry between the two walking speeds (ΔBAI) were strongly correlated to BAI MVT (Table 5). This is because the two participants with the largest asymmetry in MVT (76% and 51%) demonstrated an increase, rather than decrease, in BAI single support when walking faster. Previous research has demonstrated significant increases in support contributions from the knee-extensor muscles with increased walking speed from habitual to fast [56,57]. It would therefore follow that as the muscular demand of gait increases via increased walking speeds, the weaker amputated limb is less able to perform its role in supporting the body during single support.

This study was the first to assess the relationship of asymmetries in knee kinetics to knee-extensor strength in ITTAs. Generally, correlations were weak or non-existent. It is possible that differences in contraction mode may have limited observable correlations; while walking is a dynamic activity, we chose to use isometric knee-extensor contractions at assess muscle strength because isometric contractions are required for valid assessment of RTD [36]. Despite this, two moderate negative associations were found: between BAI knee-extensor impulse during braking at fast walking speeds and BAI MVT; and between BAI knee-extensor moment during braking at habitual speed and BAI RTD (Table 5). These negative relationships could reflect greater co-contraction of the amputated limb hamstrings in ITTAs with smaller strength asymmetries. Such muscular activity has been observed in previous studies [19,26,27,58] to aid braking and provide increased propulsion [59,60] but with the result of reducing net knee joint moments.

Limitations

The results of this study should be generalised with care, primarily due to the low sample size which reflects the lack of availability of healthy, young individuals with traumatic unilateral transtibial amputations. Additionally, it is important to note that habitual walking speed (1.3 m/s) was faster in our population than those usually reported for confident ambulatory ITTAs (walking speed, 1.01–1.20 m/s) [13,26,29], potentially due to the relatively high activity levels of most participants in this study. It is possible that the correlations observed in this study may be more exaggerated, and thus strength symmetry more important for walking speed and gait symmetry, in less active ITTAs, so future work should consider such populations. Furthermore, as correlation does not necessarily denote causation, further research should additionally explore evidence of associations between RTD asymmetry and functional capacity in ITTAs, for example via intervention studies which look to reduce RTD asymmetry and assess any associated improvements in gait symmetry or performance. Finally, while commonly used [13,61], the method of marker placement on the prosthetic-side ankle joint and lack of incorporation of the inertial properties of the prosthetic into the Plug-in-Gait model are limitations. Future work in this population should use alternative strategies (e.g. [62]) to ensure that the prosthetic foot-ankle complex is modelled appropriately to prevent under- or over-estimation of joint kinetics.

Conclusion

This study demonstrates novel evidence that RTD asymmetry, and to a lesser extent MVT asymmetry, may limit walking speed and the difference between self-selected habitual and fast speeds. We also found greater RTD asymmetry to be associated with greater vGRF asymmetry at fast walking speeds, and a greater increase in vGRF asymmetry when comparing fast to habitual walking speeds. Further work should explore whether interventions that monitor and improve RTD symmetry might benefit speed and gait asymmetry during walking.

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Tables

Table 1. Individual participant information and mean average values for 8 ITTAs. Physical activity was assessed using the International Physical Activity Questionnaire (Short Format, http://ipaq.ki.se/downloads.htm).

Participant	Age (years)	Mass (kg)	Height (cm)	Time Since Amputation (years)	IPAQ Score (MET-mins/week)	Self-Selected Walking Speed (m/s)	
						Habitual	Fast
1	29	82.3	175	5.0	9252	1.42	1.80
2	48	81.5	180	29	1813	1.36	1.75
3	38	114	185	16	4746	1.58	2.09
4	48	83.4	184	2.0	8856	1.32	1.68
5	45	106	186	*DNR*	6102	1.01	1.37
6	45	76.5	176	26	480	1.24	1.59
7	24	78.8	170	1.5	5022	1.34	1.58
8	43	54.6	165	6.0	15918	1.38	1.76
Mean	40.0	84.5	177	12.2	6524	1.33	1.70
SD	9.00	17.9	7.40	11.5	4862	0.15	0.20

IPAQ, International Physical Activity Questionnaire; MET, Metabolic Equivalents; DNR, did not respond; TSB, total surface bearing socket; PTB, patellar tendon bearing socket.

Table 2. Criteria used to establish whether walking speed should be covaried for via semi-partial or partial correlations instead of bivariate correlations, between BAI for a given strength variable and BAI for a given gait variable. A moderate relationship was defined as r≥0.5.

Bivariate	Semi-partial	Partial
Neither BAI for the strength nor the gait variable were moderately related to walking speed.	BAI for either the strength or the gait variable was moderately related to walking speed.	BAI of both variables was moderately related to walking speed.

Table 3. Absolute, relative (to bodymass, BM) and BAI values for isometric MVT and peak RTD of the knee-extensors in the amputated- and intact-limbs of ITTAs. Data are presented as group mean ± SD (n=8). Paired differences between the amputated- and intact-limbs are denoted by * (*p*<0.05) or ** (*p*<0.001),

	Amputated	Intact	BAI (%)
			Mean ± SD
MVT (Nm)	67.2 ± 24.6*	179 ± 69.9	42.2 ± 19.1
MVT_{BM} ($Nm.kg^{-1}$)	0.85 ± 0.46*	2.29 ± 1.17	
RTD ($Nm.s^{-1}$)	388 ± 217**	1529 ± 608	58.5 ± 16.2
RTD_{BM} ($Nm.s^{-1}.kg^{-1}$)	5.17 ± 4.18**	19.6 ± 9.94	

BAI, Bilateral Asymmetry Index; MVT, maximum voluntary torque; RTD, rate of torque development.

Table 4. BAI in temporo-spatial and kinetic parameters of gait between the amputated (AMP) and intact (INT) limb of ITTAs (n=8), walking at a self-selected habitual and fast speed. Data are presented as mean ± SD. Paired differences between the amputated- and intact-limbs within a given walking speed are denoted by * (*p*<0.05) or ** (*p*<0.001).

	Habitual			Fast		
	AMP	INT	BAI (%)	AMP	INT	BAI (%)
Temporo-spatial parameters						
Single support time (s)	0.41 ± 0.03**	0.44 ± 0.03	3.65 ± 2.40	0.38 ± 0.05	0.39 ± 0.05	2.35 ± 4.62
Step length (m)	0.78 ± 0.05*	0.69 ± 0.07	-6.13 ± 2.34	0.86 ± 0.07**	0.78 ± 0.06	-5.03 ± 1.62
Braking Phase Kinetic parameters						
Peak KE Moment ($Nm.kg^{-1}$)	0.27 ± 0.15*	0.68 ± 0.28	46.4 ± 24.7	0.32 ± 0.12**	1.10 ± 0.28	54.5 ± 14.3
KE Impulse ($Nm·s.kg^{-1}$)	0.0084 ± 0.0059*	0.0224 ± 0.0104	47.4 ± 35.4	0.0076 ± 0.0038**	0.0305 ± 0.0102	60.6 ± 15.3
Peak vGRF ($N.kg^{-1}$)	10.5 ± 0.70*	12.3 ± 1.36	7.76 ± 6.27	10.9 ± 1.50*	13.6 ± 1.64	10.8 ± 6.44
Propulsive Phase Kinetic parameters						
Peak vGRF ($N.kg^{-1}$)	9.51 ± 0.89*	11.5 ± 0.87	9.69 ± 5.68	9.60 ± 0.99**	12.1 ± 0.80	11.8 ± 4.44

BAI, Bilateral Asymmetry Index; KE, knee extension; vGRF, vertical ground reaction force

Table 5. Bivariate, semi-partial and partial correlation coefficients (r) between both BAI in MVT and RTD (measured during voluntary isometric contractions of the knee-extensors), and BAI in gait variables in ITTAs (n=8). BAI in gait variables were measured at a self-selected habitual and fast walking speed. Significant correlations after Benjamini-Hochberg correction are in **bold**.

	MVT			RTD		
	BAI_Habit	BAI_Fast	ΔBAI	BAI_Habit	BAI_Fast	ΔBAI
Temporo-spatial parameters						
Single support	-0.17	0.60	0.83	-0.30	0.06	0.61
Step length	0.07	0.46	0.41	0.45	0.58	0.59
Braking Phase Kinetic parameters						
Peak KE Moment	-0.45	-0.32	0.30	-0.60	0.03	-0.33
KE Impulse	-0.28	-0.56	0.01	-0.48	0.08	-0.36
Peak vGRF	-0.42	-0.29	0.36	0.10	0.54	**0.89**
Propulsive Phase Kinetic parameters						
Peak vGRF	-0.22	-0.01	0.59	0.35	0.74	**0.92**

BAI, bilateral asymmetry index; MVT, maximal voluntary torque; RTD, rate of torque development; KE, knee-extensor; vGRF, vertical ground reaction force.

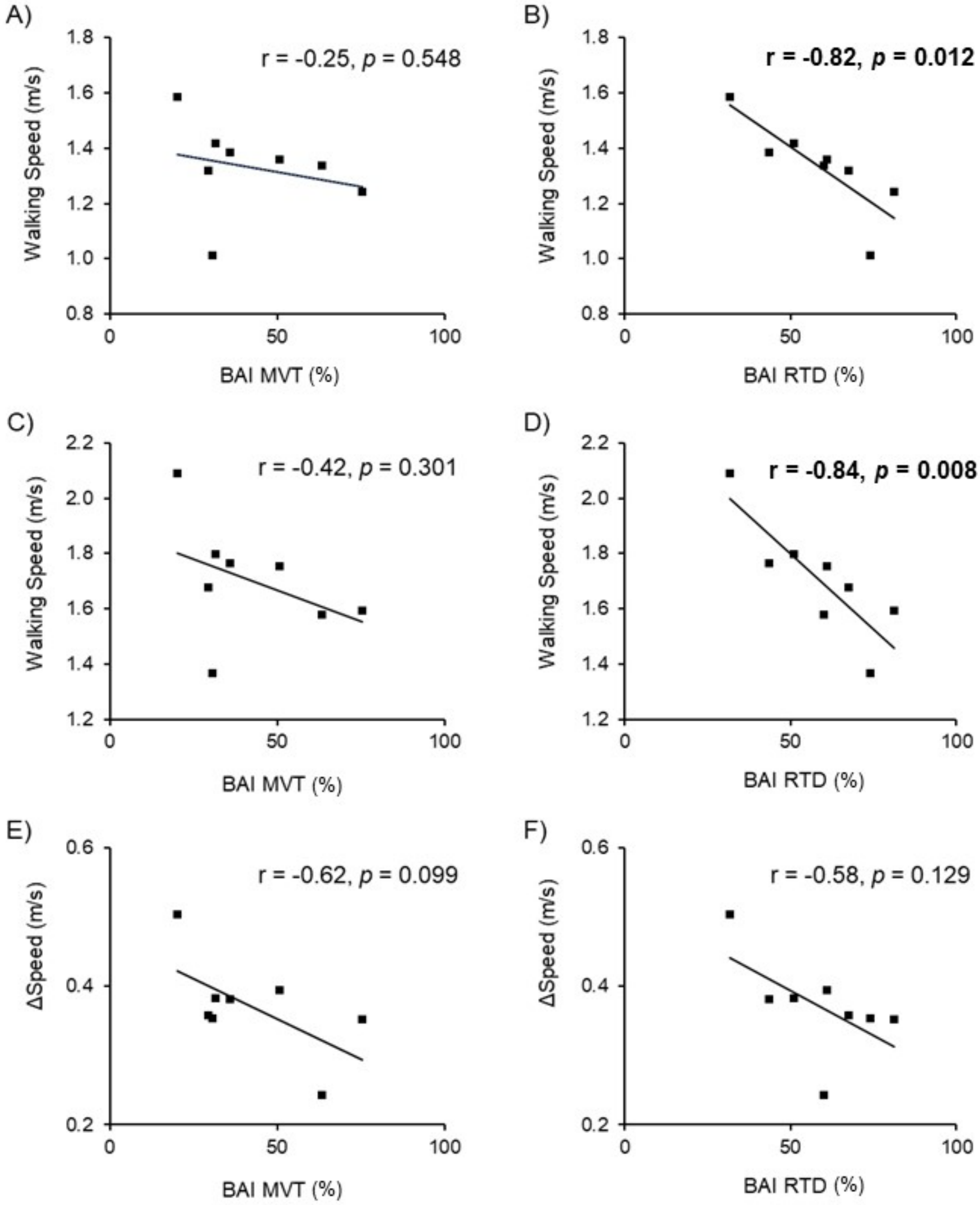

Figure 1. The relationships between walking speed and asymmetry in both maximal voluntary torque (BAI MVT) and rate of torque development (BAI RTD) of the knee-extensors, in ITTAs. Walking speed was assessed during both self-selected habitual (A and C) and fast (B and D) speeds. The difference in walking speed between habitual and fast walking (ΔSpeed; E and F) was also evaluated. Significant correlations after Benjamini-Hochberg correction are in **bold**.

Author Contributions

A.S., N.T., S.S. and S.M. conceived and designed the research; A.S and S.M. performed experiments; A.S. analysed data; A.S. and N.T. interpreted results of experiments; A.S. and N.T. drafted manuscript; A.S., N.T., S.S. and S.M. edited and revised manuscript; all authors approved final version of the manuscript. Data collection was performed in the biomechanics laboratory at the University of Roehampton, Whitelands College.