Running at submaximal speeds, the role of the intact and prosthetic limbs for trans-tibial amputees

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Research Highlights:

- The prosthetic limb brakes less rather than propels more at higher speeds
- The prosthetic limb vertical drive is reduced at higher speeds compared to control
- The intact limb brakes more compared to the prosthetic limb and control at lower speeds
- No increased vertical loading on the intact limb compared to control
- Braking and propelling peak force, step length and frequency associate with speed

Abstract

Background: Dynamic Elastic Response prostheses are designed absorb and return strain energy in running. Past research has focused on running prostheses with a single toe spring designed for high speeds.

Research Question: To determine how runners with amputation modulate the ground reaction force of each limb to run at different speeds using a general-purpose dynamic prosthesis which has a heel spring.

Methods: Overground running data were collected in 16 recreational runners (8 transtibial amputee using their own BladeXT prosthesis and 8 controls) using Vicon Nexus V.2.5 with Kistler force plates. Participants ran at self-selected running pace, 70% and 130% of that pace. Vertical, braking and propulsion peak ground reaction forces and impulses and vertical loading and decay rates were analysed between limbs at each speed (ANOVA) and their association with speed assessed (simple linear regression).

Results: The vertical, braking forces and impulses and propulsive force were significantly less ($p<0.05$) on the prosthetic limb than controls at the faster speed, but there was no difference in the propulsive impulse. The intact limb did not evidence increased vertical force at any speed, but experienced increased braking ($p<0.05$) compared to both prosthetic limb and controls at the slow speed. For all limbs, braking and propulsive peak forces, decay rate, step length and step frequency were strongly ($r>0.6$) and significantly ($p<0.05$) associated with speed. On the prosthetic limb vertical impulse was strongly and significantly negatively associated with speed and control's braking impulse was associated with speed.

Significance: A leg-specific response was found at different speeds. On the prosthetic limb the technique was to brake less not propel more at higher speeds with reduced vertical drive. Running at self-selected speed could be used for fitness without inducing detrimental ground reaction forces on the intact limb or evoking asymmetry in step length and frequency.

Key words:
running; amputee; dynamic elastic response prosthesis; ground reaction forces; ground reaction impulses

Introduction

The ability to run at submaximal speeds is important when exercising for health[1]. A variety of dynamic elastic response prostheses (DERP) have been developed to enable people with lower limb amputation to participate in running-related activities yet these passive devices cannot generate more mechanical energy than they absorb. Although there has been an increased interest in the biomechanics of amputee running, research is limited to few participants[2], sprinting[3] and treadmill running[4,5] using running-specific prostheses (RSP). RSP are dynamic prostheses designed for high-speed running with no 'heel' component and ground contact is made on the toe element. There is little research on DERP, though a prosthesis with a heel component is more likely to be prescribed for non-elite recreational runners. Using RSP, during both treadmill[5] and over-ground running[6], peak vertical forces developed by the prosthetic limb (PL) have been found to be reduced compared to the intact limb (IL) and control limbs (CL) while those on the IL are higher. It is not clear if asymmetrical loading is due to various prostheses used or to their mechanical limitations including alignment, stiffness and requirement for toe-running [4,7].

Running speed is frequently assessed by step length (SL) and frequency (SF). SL increases are the primary mechanism to run at faster sub-maximal steady-state speeds (between 3.5-7m/s) and the ankle plantarflexors play a primary role[8] with faster sprinting speeds achieved though increasing ground reaction forces[9] including their rate of development and decline. It is unclear how amputees alter SL, SF and ground reaction impulse to run at different sub-maximal speeds without a functioning ankle joint, as research is limited to imposed controlled speeds using different designs of RSP[6,10,11]. Potentially, a spontaneously self-selected running speed may be selected to optimise the mechanics of any prosthesis.

The aim of this research was to determine how the IL and PL of people with a unilateral trans-tibial amputation and the CL of a similar able-bodied group responded to run at three different submaximal steady-state running speeds based upon their self-selected running speed. We hypothesised that there would be an effect of limb (IL>CL> PL) on the force variables at each relative speed. We hypothesised that running speed would be associated with step length and frequency, vertical and braking-propulsion ground reaction forces and impulses and that there would be a limb specific response.

Methods

Eight males without any disability (age:30[6] years, mass:73.2[12] kg, height:1.77[0.05] m, Leg Length:0.93[0.04] m) and eight healthy males with a unilateral trans-tibial amputation (4 had left side amputation; age:30[8] years, mass:78.2[9] kg, height:1.81[0.06] m PL Length:0.99[0.04], IL Length:0.94[0.04] m) participated. All amputations were due to trauma and none had self-reported known issues with the residual limb or prosthetic fitting and were free from pain and skin lesions. All participants were active recreational runners (at least once a week) injury-free for at least one year. Participants completed the test using their own running shoes and/or prescribed prosthesis (Design: Blade XT, Blatchford & Sons Ltd., Hampshire, UK without cover or shoe, prescribed and used for at least 6 months). All participants provided informed consent to the University of Roehampton Review Board-approved protocol.

Three-dimensional motion of a heel marker on each foot/prosthesis, at the end of the heel-spring was obtained using a nine-camera 3D-motion capture system sampling at 120Hz (Vicon Nexus V.2.5 Oxford Metrics, Oxford, UK), synchronised with two embedded force plates (Kistler Switzerland) sampling at 1000Hz. The capture volume was approximately 9m from the start and 4m-spread timing gates (IRE emitters and IRD-T175 detectors; Brower, Draper, Utah) ensured that average running speed was maintained. Prior to testing, participants performed at least three familiarisation trials along the 20m track, to find their self-selected speed. Repeat trials were performed until three runs could be completed within 5% tolerance, then five trials were recorded at this self-selected speed. Thereafter five trials of two further running speeds: 70% (slow) and 130% (fast) of self-selected speed were recorded. Trials were discarded if the foot/prosthesis did not entirely strike or visible targeting the force plates occurred. The right limb of the control participants is reported.

Collected heel motion and force data were filtered using a fourth-order Butterworth low-pass filter (cutoff: 10Hz for motion, 300 Hz cut-off for force data). Heel marker displacement data in the forward direction were used to calculate step length, which in turn was used to calculate running speed (step length/step time). Stance was defined by a vertical GRF threshold of 10 N[12] and divided into braking and propulsion when horizontal GRF equalled zero. Peak vertical (pVF), braking (pBF) and propulsive (pPF) GRF ($N.kg^{-1}$) were extracted and horizontal braking (BI), propulsion (PI) and vertical impulses (VI) calculated by trapezoidal-rule integration. Net impulse was calculated for each individual as the difference between the BI and PI. Vertical loading (10 N to 1 BW) and decay rates (1 BW to 10N) were calculated from vertical GRF[13]. .

Data were analysed (SPSS v22.0.0.1, IBM Corp., USA) using two statistical analyses. To assess the first hypothesis, three independent analysis of variance (ANOVA) tested for differences ($p<0.05$) between the PL, IL and CL, one for each speed (Slow, Self-selected, Fast). Significant differences from the full factorial analysis were followed-up with pairwise comparisons with Bonferroni adjustments for multiple comparisons. To assess the second hypothesis, simple linear regression determined the association between the variables and actual running speed for each limb. Cohen's convention of strong (>0.6) associations and significant ($p<0.05$) are reported.

Results

The self-selected mean (SD) running speed for the amputee group was 3.0 m.s^{-1} (0.25) and for the control group was 2.8 m.s^{-1} (0.26); amputee slow speed was 2.2 m.s^{-1} (0.26) and control 2.0 m.s^{-1} (0.17); amputee fast speed was 4.0 m.s^{-1} (0.30) and control 3.6 m.s^{-1} (0.35). There were no significant differences between the groups.

***** Figure 1 about here *****

SL and SF were strongly and significantly positively associated with speed for all limbs (Figure 1), though the SF association was stronger and the slope greater for the amputees than controls. There was no significant between-limb difference in SL and SF at any speed.

****Figure 2 about here****

A main between-limb effect was found for pVF (Figure 2a) with a reduced pVF on the PL compared to the CL at self-selected ($p=0.038$) and fast speeds ($p=0.036$). There was an effect of limb at the fast speed for the VI (Figure 2b), the PL was significantly lower than the CL ($p=0.003$). There was no difference between the limbs at any speed for the vertical loading and decay rates (Figure 2c-d).

****Figure 3 about here****

For the pBF, the ANOVA indicated a main effect at all speeds (Figure 3a). The PL was significantly lower than the IL at slow speed ($p=0.00$) and than the CL and IL at self-selected (CL: $p=0.040$; IL: $p=0.004$) and fast speeds (CL: $p=0.042$; IL: $p<0.000$). The IL experienced higher pBF compared to the

CL at slow (p=0.003) speed. For the BI there was a main effect of limb at all speeds (Figure 3b). It was significantly lower on the PL compared to the IL at slow speed (p=0.00) and to the CL and IL at both self-selected (CL: p=0.001; IL: p=0.001) and fast speeds (CL: p<0.000; IL p<0.000). BI was significantly greater on the IL compared to the CL (p=0.019) at slow speed. For the pPF, there was an effect of limb at all speeds (Figure 3c). The PL experienced a significantly lower pPF compared to the CL at all speeds (Slow: p=0.004; SS: p=0.008; Fast: p=0.001) and to the IL at slow (p=0.002) and fast (p<0.000) speeds. There was no effect of limb at any speed for the PI (Figure 3d).

****Figure 4 about here****

The pVF showed a strong association with running speed only for the CL (r=0.673 p<0.000; IL: r=0.424 p=0.39; PL: r=.298 p=0.157) (Figure 4a). For the VI, a strong significant negative correlation with speed was seen only for the PL (PL: r=-.801 p<0.000; IL: r=-.532 p=0.008; CL: r=-.347 p=0.097) (Figure 4b). The decay rate was strongly and significantly related to speed (PL: r=0.770, p<0.000; IL: r=0.816, p<0.000; CL: r=0.871, p<0.000) (Figure 4d).

*** Insert Figure 5 about here****

In the horizontal direction, the pBF indicated a strong negative association for all limbs (PL: r=-.774 p<0.000; IL: r=-.629 p=0.001; CL: r=-.874 p<0.000) (Figure 5a). BI was strongly negatively associated for the CL but not the IL or PL (CL: r=-.779 p<0.000). The pPF (Figure 5c) indicated a strong positive association for all limbs (PL: r=.892 p<0.000; IL: r=.857 p<0.000; CL: r=.850 p<0.000). The PI (Figure 5d) was strongly and significantly associated for the CL (PL: r=.415 p=0.044; IL: r=.380 p=0.067; CL: r=.585 p=0.003).
The IL demonstrated a net BI at all speeds (Slow: -0.035 (0.05); self-selected -0.046 (0.065); Fast -0.0313 (0.09) N.kg^{-1}.s) while the PL demonstrated a net PI at all speeds (Slow: 0.026 (0.06); self-selected: 0.054 (0.057); Fast: 0.081 (0.047) N.kg^{-1}.s). The net impulse for the CL (Slow: 0.003 (0.04); self-selected 0.005 (0.02); Fast -0.011 (0.029) N.kg^{-1}.s) was close or at zero, indicating steady state running.

Discussion

We aimed to determine how each limb of people with a unilateral amputation responded to change steady-state submaximal running speed, given the passive nature of DERP.

Our first hypothesis was that there would be a between-limb difference in the force variables and SL and SF due to the absent active drive associated with the ankle plantarflexors[8]. On the PL, the lack of vertical drive is evidenced only at higher speeds by the lower pVF and VI compared to the CL. The reduced pBF and BI on the PL is consistent with past research suggesting that amputees adopt a vertical loading when using RSP[2,6,14]. RSP prostheses lack a heel component requiring a toe landing, which is associated with reduced braking in non-amputee runners[13] and a plantarflexed alignment[15]. Although the DERP used in our study had a short heel, the amputees also chose a landing which allowed them to not slow down during self-selected and fast running. In propulsion, the reduced pPF indicates the inability to drive in the forward direction but the timing and development of force during the phase was manipulated and there was no difference in the PI, consistent with past research[6] .

Contrary to our hypothesis for the IL, the pVF and loading rate were not greater than the CL at any speed (Fig. 2a,c). At slow speeds, the relatively low forces required to propel the body into flight are achieved by the mechanical properties of the prosthesis and the step-length and step frequency can be manipulated to maintain a symmetrical pVF. In contrast to the pVF, pBF and BI were greater for IL compared to CL at slow speed. This is may be related to the need to modulate the overall speed or step-to-step transition mechanics which suggests that the increased load on the IL is related to the diminished propulsion from the PL [16,17]. Whilst the flight phase of running removes the step-to-step transition, it is reasonable to assume that a similar mechanism which relates the contralateral propulsion with the ipsilateral loading occurs for slow running which has a short aerial phase and a speed comparable to a fast walk. Further research is justified to explore this relationship.

Our second hypothesis was that forces and impulses would increase with running speed, but that this would be limb dependent due to the inability of the PL to actively increase force. We found that four variables were strongly related to speed on the PL, three on the IL and six on the CL (Fig 4,5). On the PL, those with the strongest association with speed were pPF (R^2=0.80 (Fig5c)), VI (negative - R^2=0.64 (Fig 4b)) and pBF (negative R^2=0.60 (Fig5a)). On the IL, those with the strongest association with speed were pPF (R^2 =0.74 Fig 5c)) and pBF (negative - R^2 =0.40 (Fig5a)). On the CL, those with the strongest association with speed were pBF (negative - R^2 =0.76 (Fig5a)), pPF (R^2 =0.72 (Fig 5c)) and BI (negative - R^2 = 0.61 (Fig5b)). Horizontal peak forces were consistently associated with speed. The vertical decay rate, the unloading mechanism related to the dynamic drive to accelerate the body into flight, was strongly associated with speed, with more rapid unloading at higher speeds for all limbs. There was no effect of limb at any speed indicating that the PL can unload rapidly in spite of its passivity. The interplay between the load-recoil of the DERP and the other joints requires further investigation to understand this mechanism.

The VI is a direct measure of how the vertical momentum is altered over the stance period. We anticipated a strong positive correlation with speed, to ensure sufficient time to swing the limb through to prepare for the next stance period[9] and we had hypothesised a limb-effect. VI displayed a strong negative association with speed for the PL but not for the biological limbs. The PL could not maintain the same VI as speed increased as the prosthesis 'topped-out'. The pVF did not increase (Fig 4a) and its correlation was weakest with speed.

On the PL, the BI did not increase with speed resulting in significantly lower between-limb BI at the higher speeds. The PI increased with speed with no between-limb difference at the faster speed. These findings agree with past research on running at controlled speeds[6] and indicate a strategy to break less at higher speeds. When running at steady state, the net AP impulse should be zero, which was not the case for the amputees. At slower speeds the IL produced a greater BI compared to the PL slowing the overall speed and transitioning step-to-step while at faster speeds there was no difference in PI maintaining the faster speed and the vertical posture on the PL. The negative IL impulse was generally balanced by the positive PL impulse, resulting in a net steady state running speed.

There was a positive relationship between both SL and SF with running speed (Fig 1) with a greater reliance on SF in amputees, evidenced by a greater slope. The inability on the PL to increase vertical and propulsive forces will result both in reduced accelerations and shorter aerial times. This supports the mechanism that higher speeds will result from increased SF rather than SL, consistent with past research on amputee treadmill and over-ground running[5,6,10].

The current research design did not control speed so that the amputees could self-select their speed, most likely the most efficient and that at which they could optimise the compression-recoil of the prosthesis. At these speeds, using this prosthetic design, there is no evidence that the ground reaction forces experienced on the IL are increased compared to the CL, other than in the braking direction at slow speeds. This has important implications and suggests that submaximal running, particularly at a spontaneous self-selected speed, may be useful to incur physiological benefit without imposing detrimental ground reaction forces to the IL. Further research is required to analyse the joint kinematics and kinetics to understand their role in running and potential injury-inducing mechanisms that may ensue.

There was no significant difference between the speeds among the amputees and control participants indicating that they were well matched and that any differences are as a result of limb. . Using the same prosthetic design for all amputees indicates that differences are more likely due to amputation rather than multiple prosthetic types. Further research is required to understand the effect of a wider range of speeds on the vertical and braking-propulsive forces and impulses and their effect on SL and SF for over-ground running.

There are some potential limitations to this research, particularly relating to the small number of participants and limited number of trials assessed and the consequent under-powering of the analysis and inability to apply multivariate analysis techniques. Further, the participants were not matched exactly between groups and all participant wore their own footwear (there were no shoes on the prosthesis). The effect of limb dominance and leg length was not assessed and may influence the results, depending on which leg was amputated. Joint kinematics and kinetics were not analysed and their role in performance and potential injury-inducing movement patterns requires further investigation. There was high variability in the Loading Rate results, due to one participant in the control data and one on the IL who experienced a rapid and high impact peak which resulted in high loading rates. The method to calculate loading rate and the relevance of this variable in performance and injury requires further work.

Although the ankle has been strongly associated with speed in able-bodied runners[8], our results suggest that trans-tibial amputees can adjust submaximal running in the absence of an anatomical ankle. The relationship of specific force variables in the horizontal and vertical directions with speed indicated a leg-specific response. The amputees adopted a strategy on the PL to brake less at higher speeds. Propulsive forces and impulses were able to accommodate the change in speed such that the SL was not different between limbs though a greater reliance was placed on increasing SF to run faster. At these relatively low speeds no increased IL vertical loading but increased braking were evident at the slow speed.

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Conflict of Interest Statement

None of the authors has any conflict of interest.

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Table of abbreviations

DERP	Dynamic Elastic Response Prosthesis
RSP	Running Specific Prosthesis
PL	Prosthetic Limb
IL	Intact Limb
CL	Control Limb
SL	Step Length
SF	Step Frequency
pVF	Peak Vertical ground reaction Force
pBF	Peak Braking Ground Reaction Force
pPF	Peak Propulsive Ground Reaction Force
VI	Vertical Impulse
BI	Braking Impulse
PI	Propulsive Impulse

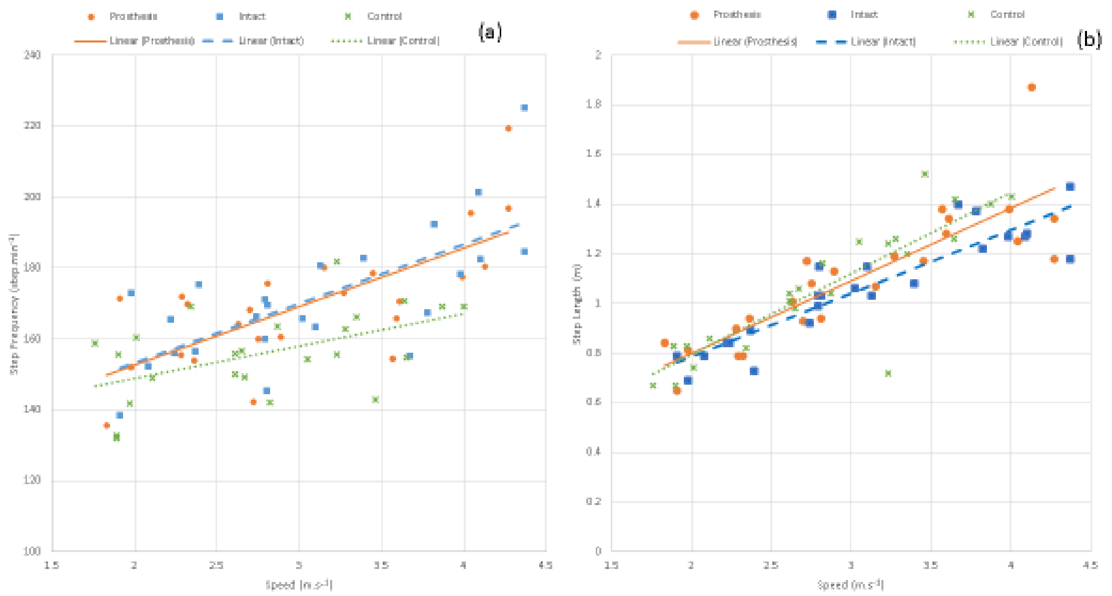
Figure 1 Average step frequency (a) and step length (b) across speed. Amputee (circle and solid line) and Control (square and dashed line) participants increased both step frequency and step length with speed however, the amputees increased step frequency to a greater extent than the control participants. The linear fit equations for step frequency were PL = 16.51x+119.62, R^2=0.50; IL = 16.7x+119.8, R^2 = 0.50; Control: 9.15x+180.5, R^2=0.27. The linear equations for step length for each leg were PL = 0.29x+0.21, R^2=0.73; IL = 0.33x+0.14, R^2=0.83; CL= 0.26x+0.27, R^2=0.76.

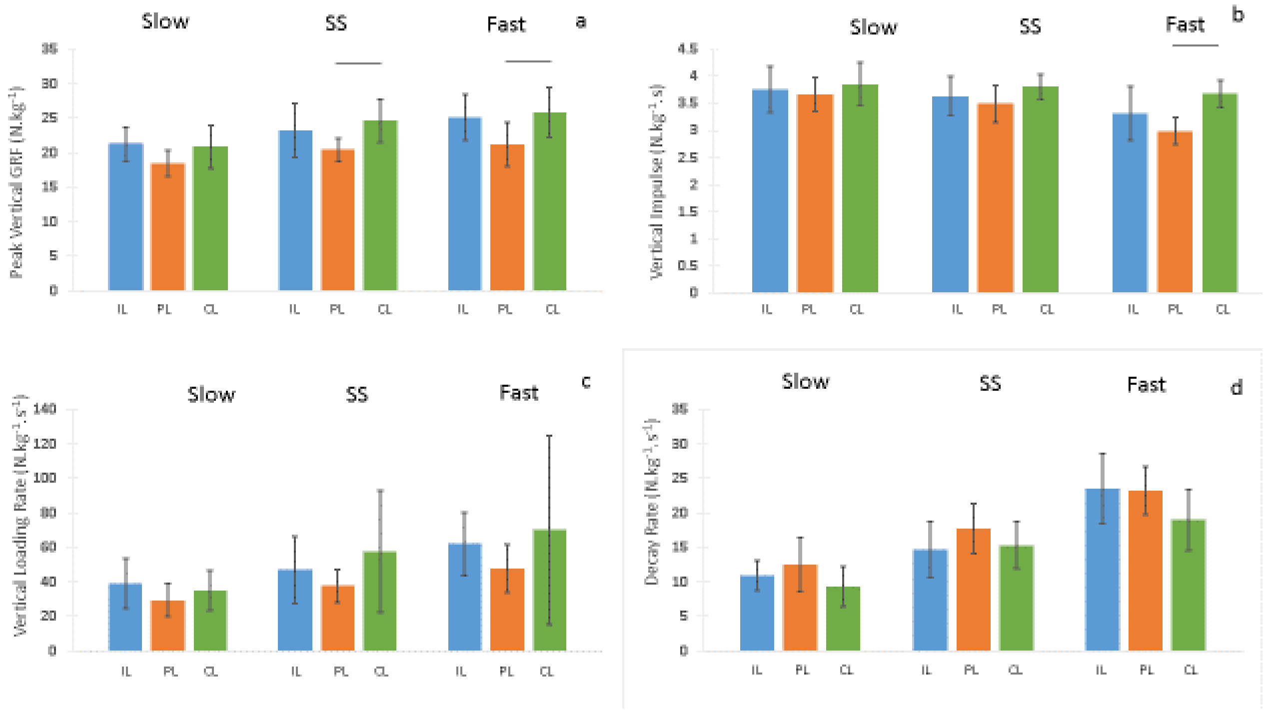
Figure 2: *Average peak vertical ground reaction force (a), vertical impulse (b), loading rate (c) and decay rate (d) for each limb at each speeds. PL peak vertical force was significantly smaller than CL at SS and Fast speeds. PL vertical impulse was significantly smaller than CL at Fast speed. There were no significant between limb differences in vertical loading or decay rates at any speed.*

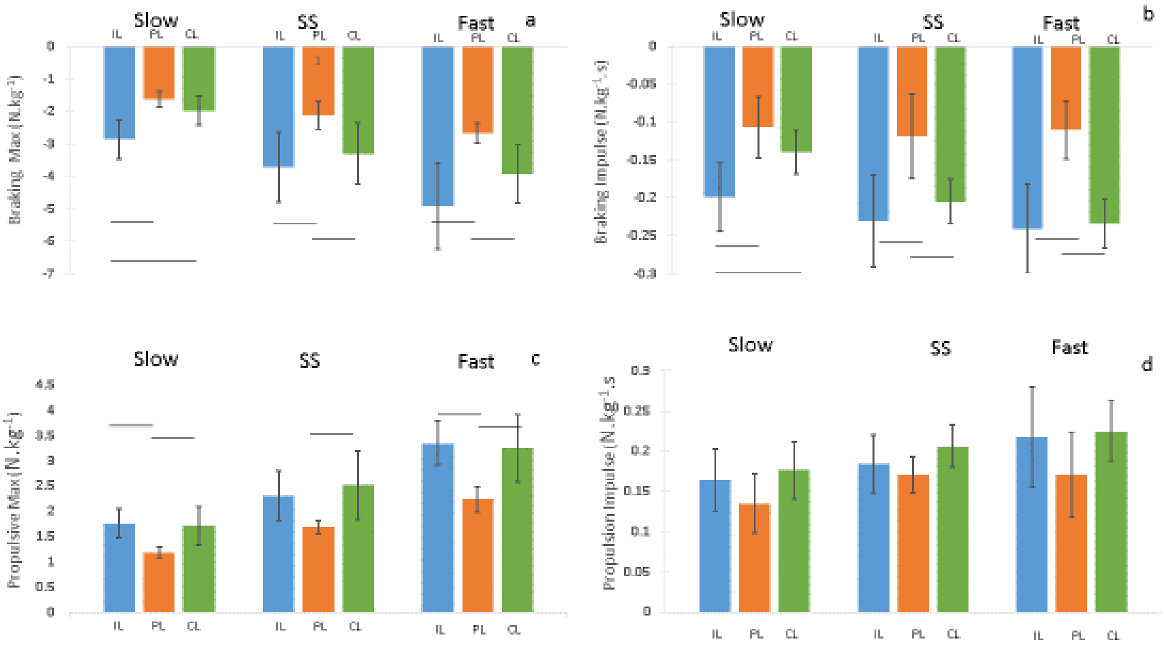
Figure 3: *Average peak braking ground reaction force (a), braking impulse (b), peak propulsive force (c) and propulsive impulse (d) for each limb at each speed. PL peak braking force was significantly smaller than IL and CL at all speeds; the IL was significantly greater than the CL at Slow and SS speeds. PL braking impulse was significantly smaller than IL and CL at all speeds. PL propulsive peak force was significantly smaller than CL at all speeds and smaller than IL at slow speed; IL was smaller than CL at the slow speed. There were no significant between limb differences in propulsive impulse at any speed.*

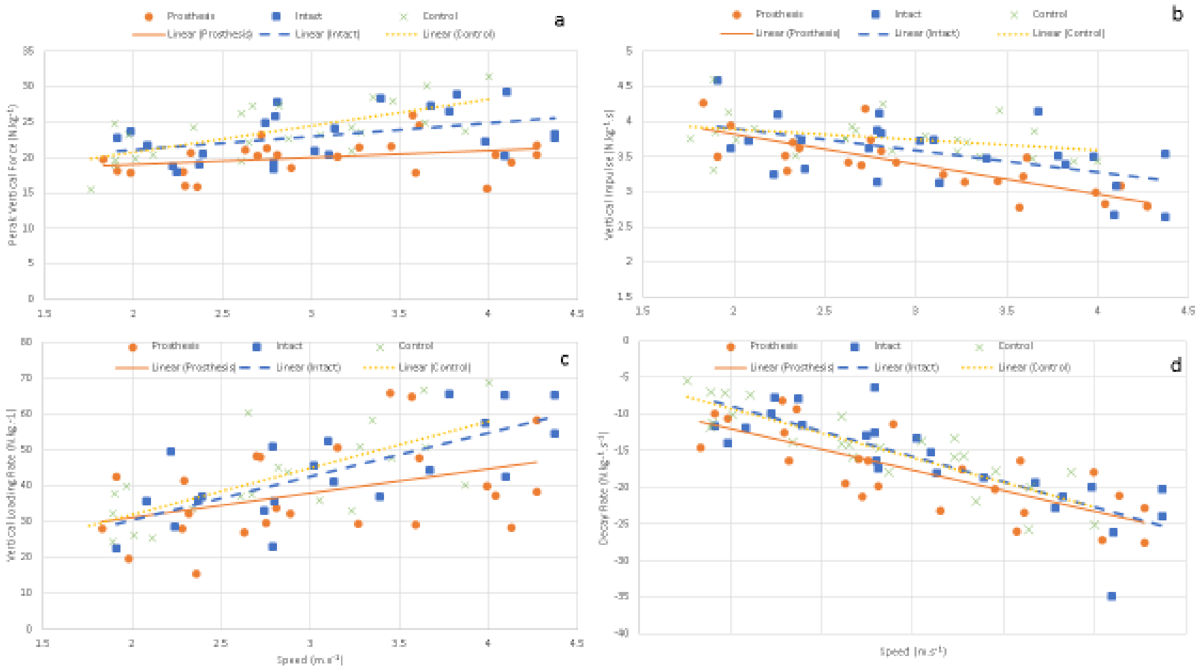
Figure 4: Average peak vertical ground reaction force (a), vertical impulse (b), loading rate (c) and decay rate (d) across absolute speed. CL increased the peak vertical force to a greater extent that the IL or PL while CL decreased the vertical impulse less than IL or PL. The vertical loading rate increased least with the PL. The decay rate became more negative with speed for all limbs, that is the unloading of the limb was more rapid across speed. The linear fit equations for peak vertical force were PL = 0.98x+17.1, R^2=0.09; IL= 1.82x+17.2, R^2=0.18; CL: 3.72x+13.39 R^2=0.45. The linear equations for vertical impulse for each leg were PL = -0.43x+4.67, R^2=0.64; IL= -0.31x+4.51, R^2=0.28; CL: -0.15x+4.19 R^2= 0.12. The linear equations for the vertical loading rate for each leg were PL = 6.82x+17.5, R^2= 0.16; IL= 12.11x+6.33, R^2= 0.19; CL: 12.95x+6.1 R^2=0.07. The linear equations for decay rate for each leg PL = -5.64x+0.72 R^2= 0.59; IL= -6.88x+4.82, R^2=0.67; CL: -6.74x+4.26 R^2= 0.76. PL – circle and solid line, IL – square with long dash, CL - x and dots.

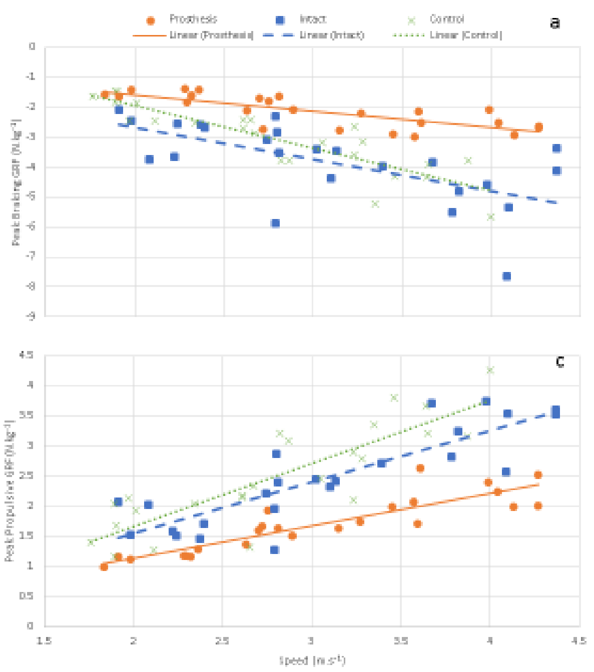
Figure 5 Average Antero-posterior forces and impulses across absolute speed. Peak force in braking (a) and braking impulse (b) showed a reduced association with speed for the PL. Peak propulsive force (c) and Impulse (d) were positively associated with speed for all limbs. The linear fit equations *for peak braking force were PL = -0.45x-0.51,* $R^2 = 0.60$*; IL = -1.05x-0.58;* $R^2 = 0.40$*; CL = -1.42x+0.88,* $R^2=0.76$*. The linear fit equations for the braking impulse were PL = 0.00x-0.11;* $R^2=0.00$*; IL = -0.06x-0.04,* $R^2 = 0.61$*; CL= -0.02x-0.17,* $R^2 = 0.07$*. The linear fit equations for peak propulsive force were PL= 0.54x+0.06,* $R^2=0.80$*; IL = 0.85x-0.15,* $R^2 = 0.74$*; CL = 1.04x-0.42,* $R^2 = 0.72$*. The linear fit equations for the propulsive impulse were PL = 0.02x+0.09,* $R^2=0.17$*; IL = 0.024x+0.11,* $R^2 = 0.14$*; CL = 0.032x+0.11;* $R^2=0.34$*.*


Prosthesis
Intact
Control
Linear (Prosthesis)
Linear (Intact)
Linear (Control)
(a)
Step Frequency (step.min-1)
240
220
200
180
160
140
120
100
1.5
2
2.5
3
3.5
4
4.5
Speed (m.s-1)
(b)
Step Length (m)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Speed (m.s-1)


Slow
SS
Fast
a
Peak Vertical GRF (N.kg-1)
35
30
25
20
15
10
5
0
IL
PL
CL
b
Vertical Impulse (N.kg-1.s)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
c
Vertical Loading Rate (N.kg-1.s-1)
140
120
100
80
60
40
20
0
d
Decay Rate (N.kg-1.s-1)
35
30
25
20
15
10
5
0


a
Slow
SS
Fast
IL
PL
CL
Braking Max (N.kg^{-1})
0
-1
-2
-3
-4
-5
-6
-7
b
Braking Impulse (N.kg^{-1}.s)
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
c
Propulsive Max (N.kg^{-1})
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
d
Propulsion Impulse (N.kg^{-1}.s)
0.3
0.25
0.2
0.15
0.1
0.05
0


a
Prosthesis
Intact
Control
Linear (Prosthesis)
Linear (Intact)
Linear (Control)
Perak Vertical Force (N.kg^{-1})
35
30
25
20
15
10
5
0
1.5
2
2.5
3
3.5
4
4.5
b
Vertical Impulse (N.kg^{-1}.s)
5
4.5
4
3.5
3
2.5
2
1.5
c
Vertical Loading Rate (N.kg-1)
80
70
60
50
40
30
20
10
0
Speed (m.s^{-1})
d
Decay Rate (N.kg^{-1}.s^{-1})
0
-5
-10
-15
-20
-25
-30
-35
-40
Speed (m.s^{-1})


Prosthesis
Intact
Control
Linear (Prosthesis)
Linear (Intact)
Linear (Control)
a
Peak Braking GRF (N.kg^{-1})
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
b
Braking Impulse (N.kg^{-1}.s)
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
-0.35
-0.4
1.5
2
2.5
3
3.5
4
4.5
c
Peak Propulsive GRF (N.kg^{-1})
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
d
Propulsive Impulse (N.kg^{-1}.s)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1.5
2
2.5
3
3.5
4
4.5
Speed (m.s^{-1})