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Title:

Impaired heel to toe progression during gait is related to reduced ankle range of motion in people with Multiple Sclerosis

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Background: Gait impairment in people with Multiple Sclerosis results from neurological impairment, muscle weakness and reduced range of motion. Restrictions in passive ankle range of motion can result in abnormal heel-to-toe progression (weight transfer) and inefficient gait patterns in people with Multiple Sclerosis. The purpose of this study was to determine the associations between gait impairment, heel-to-toe progression and ankle range of motion in people with Multiple Sclerosis.

Methods: Twelve participants with Multiple Sclerosis and twelve healthy age-matched participants were assessed. Spatiotemporal parameters of gait and individual footprint data were used to investigate group differences. A pressure sensitive walkway was used to divide each footprint into three phases (contact, mid-stance, propulsive) and calculate the heel-to-toe progression during the stance phase of gait.

Findings: Compared to healthy controls, people with Multiple Sclerosis spent relatively less time in contact phase (7.8% vs 25.1%) and more time in the mid stance phase of gait (57.3% vs 33.7%). Inter-limb differences were observed in people with Multiple Sclerosis between the affected and non-affected sides for contact (7.8% vs 15.3%) and mid stance (57.3% and 47.1%) phases. Differences in heel-to-toe progression remained significant after adjusting for walking speed and were correlated with walking distance and ankle range of motion.

Interpretation: Impaired heel-to-toe progression was related to poor ankle range of motion in people with Multiple Sclerosis. Heel-to-toe progression provided a sensitive measure for assessing gait impairments that were not detectable using standard spatiotemporal gait parameters.

Keywords: Heel – Toe sequence, Footprint, Ankle Rocker, Electronic walkway, Gait Impairment

1. Introduction

Multiple Sclerosis (MS) is a chronic neurodegenerative disease that effects over 23,000 people in Australia (Australian Bureau of Statistics, 2012). People with Multiple Sclerosis (PwMS) identify restrictions in gait as their most common and problematic concern (Heesen et al., 2008; Hobart, Riazi, Lamping, Fitzpatrick, & Thompson, 2003). Similar to patients with cerebral palsy (CP) and stroke (Schmid, Schweizer, Romkes, Lorenzetti, & Brunner, 2013), gait impairments in PwMS may result from neurological impairments, muscle weaknesses and reduced ankle range of motion (RoM), often referred to as “joint contractures” (Hoang, Gandevia, & Herbert, 2013). Ankle joint contractures are common in PwMS and are associated with impaired walking ability.

Healthy gait is defined by regular heel-to-toe progression (weight transfer) that facilitates efficient locomotion. Heel-to-toe progression refers to foot movement that begins with heel contact and ends with toe off. Effective heel-to-toe progression is essential in preserving momentum during the stance phase of gait and is influenced by functional ankle and foot rockers (Perry, Burnfield, & Cabico, 1992). Ankle rocking during the stance phase of gait acts as a pivot point to allow for tibial progression. Adequate passive ankle dorsiflexion is needed to allow for forward progression of the tibia over the foot (Perry et al., 1992). Normal heel-to-toe progression is compromised by ankle contractures (Maurer et al., 1995) and can result in inefficient compensation strategies (such as knee hyperextension) often evident in people with neurological conditions (Schmid et al., 2013).

Heel-to-toe progression can be measured using force platforms and 3D motion capture systems. However, such analysis may be time consuming and limited to a few steps making it less practical for clinical settings (van den Noort, Ferrari, Cutti, Becher, & Harlaar, 2013). In lieu, gait impairments are often assessed using observational rating scales, which may lack sensitivity to detect subtle changes in gait patterns (Spain et al., 2012). Portable electronic walkways overcome these limitations and have been used to quantify spatiotemporal gait patterns (e.g. step length, step time and stepping variability) in PwMS (Sosnoff, Weikert, Dlugonski, Smith, & Motl, 2011) and for footprint analysis in healthy people (Titianova, Mateev, & Tarkka, 2004).

The purpose of this study was to determine the associations between gait impairment, heel-to-toe progression and ankle RoM in PwMS. A novel method of footprint analysis was used to provide information about how abnormal heel-to-toe progression may affect mobility in people with and without MS during a six-minute walk test (6MWT). Accurate assessment of heel-to-toe progression in the clinical setting could help inform rehabilitation aimed at improving functional mobility in a variety of neurologically gait impaired populations.

2. Methods

2.1 Participants

Twelve healthy participants (four males and eight females) and twelve participants with MS (three males and nine females) took part in the study. Healthy participants were matched where possible for age, sex, height and body mass (Table 1). Inclusion criteria for eligible participants in the MS group included; i) a confirmed diagnosis of MS by a neurologist; ii) An Expanded Disability Status Scale (EDSS) of ≤ 6 and able to walk independently; iii) no relapses within the past 12 weeks; iv) free from any other disease, injury or illness preventing them from participating in a 6MWT. Participants were excluded from the study if they required the use of a foot-ankle orthosis as such devices interfere with normal heel-toe sequencing. All healthy controls were free from disease, injury or illness that affected gait. The study was approved by the Human Studies Ethics Committee at the University of New South Wales. Informed consent was obtained from all participants prior to participation.

2.2 Ankle Range of Motion Assessment

Adequate RoM is essential for normal, efficient locomotion. As ankle RoM can influence heel-to-toe progression (Maurer et al., 1995), passive RoM was measured on the more affected side in PwMS to assess the overall RoM available at the ankle joint. Joint contractures are often assessed in the clinic using passive ankle RoM (Diong et al., 2012; Kwah et al., 2012). Briefly, 100N of pulling force was applied to the heads of the metatarsals, parallel to the shank and the ankle angle was measured using an inclinometer (Rippstein - Plurimeter).

2.3 Gait assessments

Participants completed a 6MWT wearing comfortable footwear at a self-selected fast walking speed on a twenty-metre walking pathway. A standard protocol was used. Participants were instructed “to walk as far as possible for 6 minutes”. Participants were reminded that they would be walking for 6 minutes and could stop and rest if needed. Participants were given standardised encouragement after each minute. A six-metre long GAITRite™ mat was positioned four metres from the start of the walking pathway to ensure normal gait patterns had resumed after each turn. Spatiotemporal measures were collected along with the footprint data of each step and exported for subsequent analysis. Multiple passes over the measurement area were combined for each participant.

2.4 Heel-to-toe progression

Only complete foot prints were used in the analyses. Each footprint was divided into three equal areas that defined the heel, mid-foot and forefoot sensors (Figure 1). Sensor activation and deactivation data for each were then used to calculate the Contact, Mid Stance and Propulsive phases of gait (Figure 1). Contact phase began with heel strike and terminated with forefoot loading and contact duration was calculated by subtracting the ‘heel on’ time from the ‘toe on’ time. Mid stance phase began with forefoot loading and terminated at heel lift and duration was calculated by subtracting ‘toe on’ time from ‘heel off’ time. The propulsive phase began with heel lift and terminated at toe off and was calculated by subtracting ‘heel off’ time from ‘toe off’ time. The phase durations were then normalised by dividing by total foot contact time and gait phases were reported as a percentage for the subsequent statistical analysis.

2.4 Statistical Analysis

Analyses were performed with SPSS statistical package (version 23). Analysis of variance (ANOVA) was used to assess group differences in heel-to-toe progression and mobility measures for people with and without MS and between affected and non-affected sides for PwMS. Post-hoc t-tests and effect sizes, Cohen’s *d* (Cohen, 1992) were calculated to assess between group differences. Because a large effect

for gait velocity was observed ($d=-1.82$, Table 1), analysis of covariance (ANCOVA) was further undertaken to determine if the group differences remained significant after adjusting for walking speed. Pearson's correlations were used to investigate any associations between heel-to-toe progression and participant demographics. Significance was set at $p < 0.05$ for all comparisons. A post-hoc power analysis (two tailed, $p = .05$) was conducted with the program *G*Power* (Faul, Erdfelder, Lang, & Buchner, 2007) to ascertain if our study was sufficiently powered to detect the group differences in 6MWT performances.

3. Results

PwMS had similar demographics to the healthy controls (Table 1), but had significantly reduced passive ankle RoM (87.9° vs 96.6°) and shorter six-minute walk distances (330m vs 506m). The average EDSS of PwMS was 4.1 (SD=1.2) representing a moderate level of disability.

With respect to the spatiotemporal assessments, PwMS walked significantly slower (1.02ms^{-1} vs 1.57ms^{-1} , $d=-1.82$) with lower cadence (98.8steps/min vs 121.2 steps/min, $d=-1.49$), shorter step lengths (61.5cm vs 77.5cm, $d=-1.71$) and longer stance times (0.08s vs 0.61s, $d=1.43$) than the healthy controls. However, the differences in cadence, step length and stance time did not remain significant after adjusting for using ANCOVA (Table 2).

With respect to quantifying heel-to-toe progression, PwMS spent a lower proportion of stance time in the contact phase (7.8% vs 25.1%, $d=-3.21$) and a greater proportion of time in the mid stance phase (57.3% vs 33.7%, $d=2.61$) than the healthy controls. The large effects (Cohen, 1992) of MS on heel-to-toe progression remained significant after adjusting for walking speed using ANCOVA (Table 2). Furthermore, in PwMS, significant differences between the affected and non-affected side were only observed in the assessment of heel-to-toe progression (Figure 2 & 3). Compared to the non-affected side, on the affected side PwMS spent a lower proportion of stance time in contact phase (7.8% vs 15.3%, $d=-1.33$) and a greater proportion in mid stance phase (57.3% vs 47.1%, $d=0.91$).

The post hoc power analysis was based on the observed differences in 6MWT distances (176m, Table 1), pooled standard deviation (99m) and the mean performance of the healthy controls (506m). The effect of MS on walking distance ($d=-1.78$) was large (Cohen, 1992). The power to detect an effect of this size in the present study comprising PwMS ($n=12$) and healthy controls ($n=12$) was high (>98%). This indicates the study was sufficiently powered to investigate gait differences between people with and without MS.

With respect to the participant demographics and background clinical assessments (Table 1) poor heel-to-toe progression was associated with reduced ankle passive RoM and shorter 6MWTs but not with differences in sex, age, height, weight or BMI. A reduction in the contact phase of gait was significantly ($p\leq 0.05$) correlated with decreased 6MWT distances ($r^2= 0.42$) and decreased passive range of ankle motion ($r^2= 0.18$). An increase in the mid-stance phase of gait was significantly ($p\leq 0.05$) correlated with decreased 6MWT distances ($r^2= 0.64$) and decreased range of ankle motion ($r^2= 0.17$).

4. Discussion

People with Multiple Sclerosis develop restrictions in ankle RoM that results in abnormal gait patterns. This study aimed to identify the associations between gait impairment, heel-to-toe progression and ankle RoM in PwMS. Results demonstrated that heel-to-toe progression is impaired in PwMS. Compared to healthy controls, PwMS spent relatively less time in the contact phase and more time in the mid-stance phase of gait. The large effect sizes observed for both the contact phase ($d=-3.21$) and the mid-stance phase of gait ($d=2.61$) indicates the potential clinical utility of assessing heel-to-toe progression objectively. In our study, the impaired heel-to-toe progression in PwMS was correlated with reductions in both passive ankle RoM and 6MWT distance ($r^2= 0.17$ to 0.64), highlighting a plausible functional pathway between clinically assessed contracture (reduced passive ankle RoM), inefficient gait patterns and reduced mobility in PwMS.

Consistent with previous research, PwMS completed a significantly shorter 6MWT distance, walked slower with lower cadences, took shorter steps and spent more time in the stance phase of gait (Givon, Zeilig, & Achiron, 2009; Sosnoff et al., 2011). Asymmetric spastic para-paresis is a common gait pattern

in PwMS (Stevens, Goodman, Rough, & Kraft, 2013) and side to side variability is often reported (Benedetti et al., 1999). However, in the current study, significant differences between the affected and non-affected sides were only observed in measures of heel-to-toe progression; percentage contact time and percentage mid stance, but not in measures of step length or stance time as previously suggested to be common in neurological populations such as MS (Benedetti et al., 1999) and Stroke (Patterson, Gage, Brooks, Black, & McIlroy, 2010).

The objective assessment of heel-to-toe progression had two main advantages over the traditional spatiotemporal parameters of cadence, step length and stance time. Firstly, differences were detected between the affected and non-affected limbs and secondly, differences remained significant after adjusting for walking speed. Together this suggests that the quantification of heel-to-toe progression may reveal subtle gait abnormalities related to gait symmetry that assessment of step lengths and stance times may not detect.

It has previously been reported that ankle joint contractures can influence gait patterns (Hoang et al., 2013), and that abnormal heel-to-toe progression can result from reduced RoM at the ankle joint (Maurer et al., 1995). Consistent with these findings, we found PwMS had significantly reduced passive RoM at the ankle when compared to healthy controls. Reduced passive ankle RoM was moderately correlated with both the reduction in the contact phase of gait ($r^2 = 0.18$) and the increase in the mid-stance phase of gait ($r^2 = 0.17$). Furthermore, we found decreased 6MWT performances were strongly correlated with both the reduction in the contact phase of gait ($r^2 = 0.42$) and the increase in the mid-stance phase of gait ($r^2 = 0.64$). Impaired heel-to-toe progression potentially provides a functional link between ankle joint contractures and mobility limitations in PwMS and therefore may offer a new target for rehabilitation.

Effective heel-to-toe progression is essential for maintaining momentum and efficiency during gait (Perry et al., 1992). Contact support period in our analysis was terminated with forefoot loading. The rapidity of this loading or plantarflexion at initial contact (IC) is regulated by the pretibial muscles including the tibialis anterior, extensor hallucis longus and extensor digitorum longus. Our results also demonstrated a

significant difference between affected (7.8%) and non-affected (15.3%) limbs throughout the contact phase of stance which was potentially caused by a combination of weakness associated with the pretibial muscles and restrictions in ankle RoM commonly observed in PwMS (Hoang et al., 2013; Perry et al., 1992).

The reduction of time spent in the contact phase was inversely associated with greater time spent in the mid-stance phase. The significant increases detected between the affected (57.3%) and non-affected (47.1%) limbs during the mid-stance phase of gait can alter forward progression and result in compensation strategies such as knee hyperextension to aid with locomotion (Schmid et al., 2013). The propulsive phase of gait demonstrated no significant differences between PwMS and healthy controls suggesting PwMS may employ a variety of compensatory gait strategies such as vaulting which could influence the amount of time spent in this period leading up to toe off.

We acknowledge certain study limitations. First, our cohort included participants with an average EDSS score of 4.1 (SD=1.2) representing a moderate level of disability within the MS population. Therefore, care must be taken with generalising our findings to MS populations with higher EDSS scores because the severity of the disease can influence gait patterns and may affect heel-to-toe progression. Second, our small sample size (n=24) was relatively small. However, the post-hoc power analysis revealed our study was sufficiently powered to investigate group differences because the effects of MS on walking ability were large. Further investigation is now required to better understand the mechanism causing the inter-limb differences in heel-to-toe progression. Specifically, it was a limitation that only passive ankle RoM was assessed and future research should also investigate the relationship between active ankle RoM during walking and heel-to-toe progression. Future research could also investigate the sensitivity of heel-to-toe progression to changes in gait associated with other neurological conditions such as Stroke and Parkinson's disease and determine if targeted interventions can modify heel-to-toe progression and therefore improve mobility.

5. Conclusions

In summary, the study findings demonstrate that objective assessment of heel-to-toe progression during a six-minute walk test identified functionally and clinically important differences in the gait of people with multiple sclerosis and potentially provides a new target for improving mobility in PwMS.

Acknowledgements

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Table 1

Participant characteristics, passive ankle range of motion and six-minute walking distance for people with MS and health controls

	People with MS		Healthy Controls		ANOVA
	Mean	SD	Mean	SD	p-value
Sex (male=1)	1.75	0.45	1.67	0.49	0.67
Age [years]	52.0	9.1	55.8	12.23	0.40
Height [m]	1.69	0.06	1.65	0.09	0.21
Mass [kg]	71.5	17.9	72.3	9.91	0.89
BMI [kg/m²]	25.1	5.7	26.8	3.34	0.39
Passive Ankle RoM [°]	87.9	7.8	96.6	5.92	0.006
6MWT [m]	330	112	506	82.64	<0.001

Table 2

Heel-to-toe progression, spatiotemporal and mobility measures assessed during the six-minute walk test for people with MS and healthy controls.

	MS		Healthy Control		ANOVA	ANCOVA	Effect sizes Cohen's d							
	Mean	SD	Mean	SD	p-value	p-value								
Mobility measures														
<i>Velocity [m/s]</i>	1.02	0.35	1.57	0.24	< 0.001	N/A	-1.82							
<i>Cadence [steps/min]</i>	98.8	20.1	121.2	6.8	0.001	0.83	-1.49							
	1. MS Affected		2. MS Non Affected		3. Healthy Controls		ANOVA	ANCOVA	Post-hoc t-tests & Effect sizes Cohen's d					
	Mean	SD	Mean	SD	Mean	SD	p-value	p-value	1 vs 2	d	1 vs 3	d	2 vs 3	d
Heel-to-Toe progression														
<i>% Contact*</i>	7.8	5.1	15.3	6.1	25.1	5.8	<0.001	<0.001	0.004	-1.33	<0.001	-3.21	0.001	-1.63
<i>% Mid Stance**</i>	57.3	12.6	47.1	9.4	33.7	8.8	<0.001	0.005	0.03	0.91	<0.001	2.16	0.002	1.47
<i>% Propulsion***</i>	34.9	10.8	37.6	7.6	41.2	6.6	0.21	0.69	0.48	-0.29	0.10	-0.70	0.23	-0.50
Spatiotemporal measures														
<i>Step Length [cm]</i>	61.5	9.5	60.5	11.3	77.5	9.2	<0.001	0.78	0.83	0.09	<0.001	-1.71	0.001	-1.64
<i>Toe Out [°]</i>	10.3	6.4	6.6	10.0	4.4	5.4	0.17	0.42	0.29	0.45	0.02	0.99	0.52	0.27
<i>Stance Time [s]</i>	0.80	0.17	0.88	0.23	0.61	0.05	0.002	0.11	0.36	-0.38	0.002	1.43	0.001	1.56

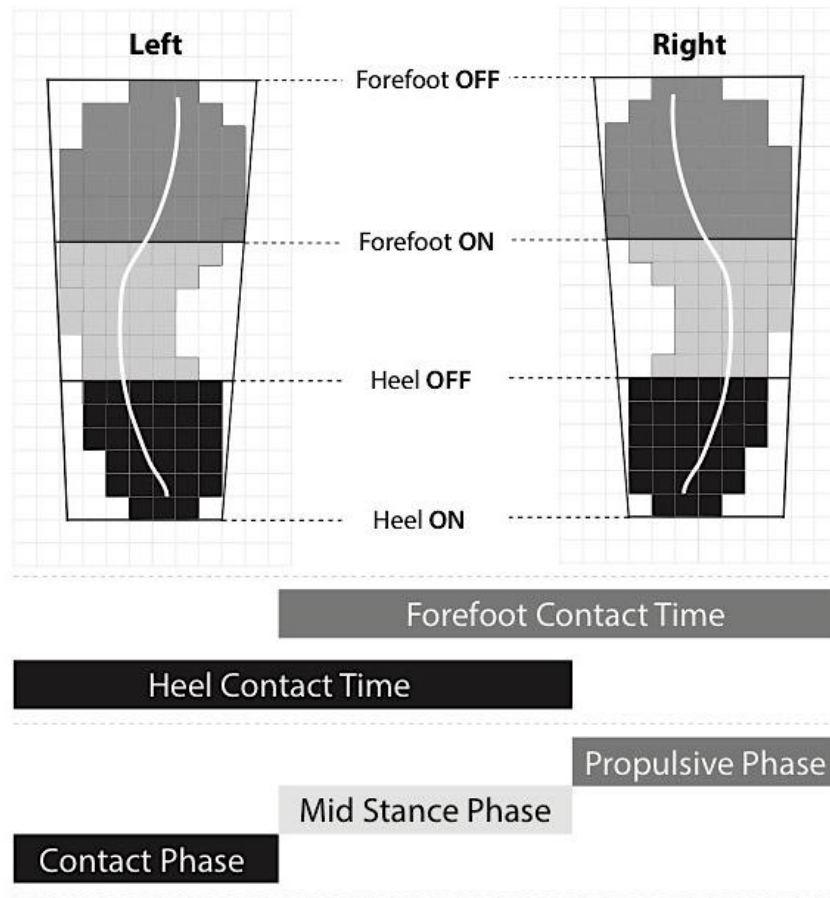
ANCOVA – Analysis of covariance adjusting for walking speed.

*% **Contact** - Time between heel loading and forefoot loading (Toe On – Heel On / Total Time)

% **Mid Stance - Time between forefoot loading and heel lift (Heel Off – Toe On / Total Time)

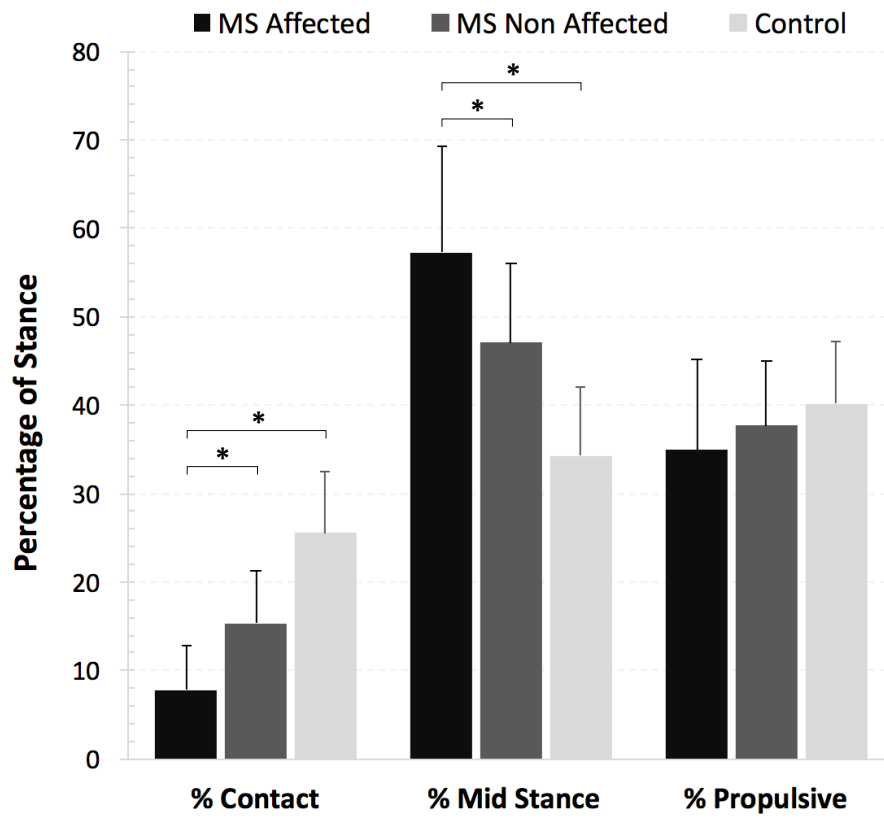
***% **Propulsion** - Time between heel lift and toe off (Toe Off – Heel Off / Total Time)

Figure 1
GAITRite™ Footprint Analysis



The contact phase begins with heel ON and is terminated with forefoot ON. The mid stance phase begins with forefoot ON and is terminated at heel OFF. The propulsive phase begins with heel OFF and is terminated at forefoot OFF.

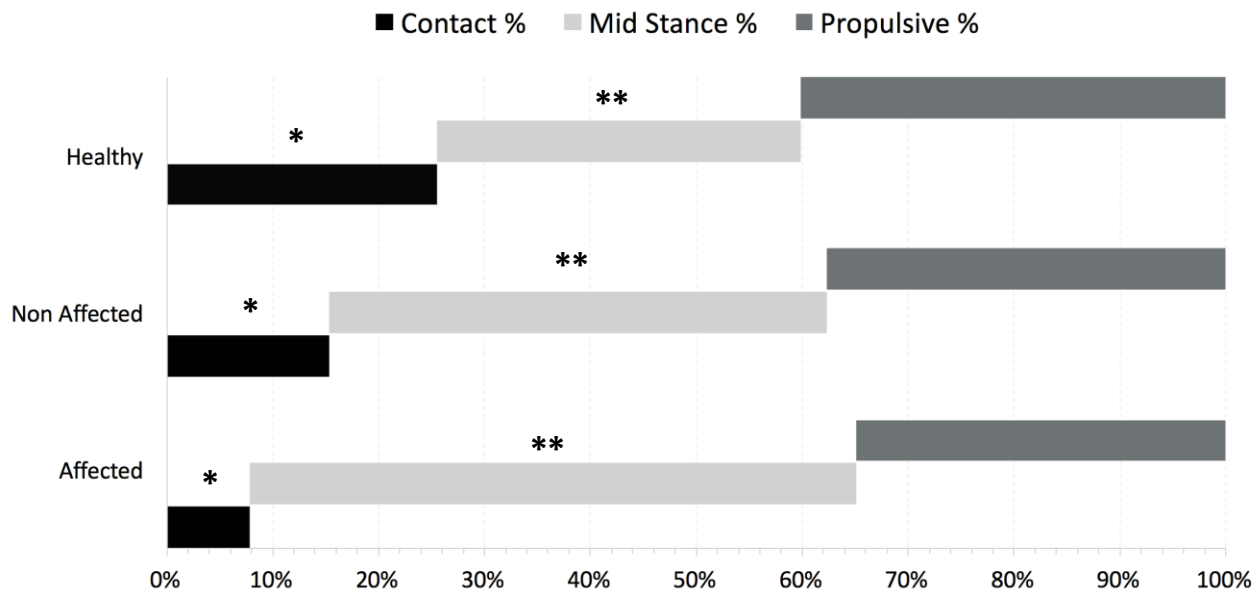
Figure 2
Stance phase percentages



*Significant difference in % Contact and % Mid stance between affected, non-affected and healthy groups.

Figure 3

Heel-to-toe progression during stance



*Significant difference in Contact % between affected, non-affected and healthy groups.

**Significant difference in Mid Stance % between affected, non-affected and healthy groups.

REVISED HIGHLIGHTS

- Heel-to-toe progression was measured in people with and without multiple sclerosis.
- In people with multiple sclerosis, heel-to-toe progression was severely compromised.
- Impaired heel-to-toe progression was related to poor ankle range of motion.
- The new test revealed functionally and clinically important inter-limb differences.
- Heel-to-toe progression is a sensitive measure to detect gait abnormalities.

ACCEPTED MANUSCRIPT