Vector-field statistics for the analysis of time varying clinical gait data

*Donnelly, C.J.[1], Alexander, C. [1], Pataky, T.C.[2], Stannage K.[3], Reid, S.[1] and Robinson M.A.[4]

[1]School of Sport Science Exercise and Health, The University of Western Australia, Perth, WA;
[2]Department of Bioengineering, Shinshu University, Japan;
[3]Department of Orthopaedics, Princess Margaret Hospital for Children, Perth, WA;
[4]Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, UK.

As accepted for publication in Clinical Biomechanics

Abstract

Background. In clinical settings, the time varying analysis of gait data relies heavily on the experience of the individual(s) assessing these data. Though three dimensional kinematics are recognised as time varying waveforms (1D), exploratory statistical analysis of these data are generally carried out with multiple discrete or 0D dependent variables. In the absence of an *a priori* 0D hypothesis, clinicians are at risk of making type I and II errors in their statistical analyses, which is why subjective analyses of these signals in addition to, or in place of statistics are used in clinical settings. The aim of this communication was to determine if vector field waveform statistics were capable of providing quantitative corroboration to practically significant difference as determined by two clinically trained gait experts. ***Methods***. The case study was a left hemiplegic Cerebral Palsy (GMFCS I) gait patient following a botulinum toxin (BoNT-A) injection to their left gastrocnemius muscle. ***Findings.*** When comparing the subjective assessments between the two testers, they were in agreement with each other for 61% of the joint degrees of freedom and phases of motion analysed. For tester 1 and tester 2, they were in agreement with the vector-field analysis for 78% and 53% of the variables analysed. When the subjective analyses of tester 1 and tester 2 were pooled together and then compared to the vector-field analysis, they were in agreement for 83% of the time varying kinematic variables analysed. ***Interpretation.*** These outcomes demonstrate that in principle, vector-field statistics corroborates with what a team of clinical gait experts would classify as practically meaningful pre- versus post time varying kinematic differences. The potential for vector-field statistics to be used as a useful clinical tool for the objective analysis of time varying clinical gait data is established. Future research is recommended to assess the usefulness of vector-field analyses during the clinical decision making process.

Key words: kinematics; lower-limb; biomechanics; statistical parametric mapping; SPM

***Corresponding Author:** Dr Cyril Donnelly, The University of Western Australia, Perth, Western Australia, 6009. P:+61 8 6488 3919|F: +61 8 6488 1039|e: cyril.donnelly@uwa.edu.au

1.0 Introduction:

There is little argument that three dimensional joint kinematics and force data are time varying (1D) vector waveforms. In clinical settings, the commonplace analysis of time varying clinical gait data is subjective, relying heavily on the experience of the individual(s) assessing these data. Though recognised as waveform data, the exploratory statistical analyses of clinical gait data are generally carried out using a variety of discrete, zero-dimensional (0D) dependent variables (i.e., min, max, mean, etc.) in an attempt to best model the time varying (1D) characteristic of these signals.

When gait waveforms are objectively assessed to determine the efficacy of a treatment in a research setting, the statistical analyses of these three dimensional or multi-component vectors are generally modelled with 0D variance about fixed means within pre-defined joint degrees of freedom and phases of the gait cycle (Ebert et al., 2013). From a scientific viewpoint, if no *a prior* 0D hypotheses is presented, and the 1D gait waveform is modelled with 0D randomness, researchers are predisposed to making *regional focus biases* in their statistical analysis (Pataky et al., 2013) and virtually guaranteed to make type I errors in their assessment of discrete (0D) time points within the waveform (Pataky et al., 2016b). They are also at-risk of making type II errors at every other time point within the time series (Pataky et al., 2013). This places practical limitations on the type(s) of quantitative analyses a clinician can use to formulate reliable clinical assessments on the effectiveness or efficacy of a given treatment or intervention.

Following the development of vector-field analysis for the mapping of human brain activity and anatomy (Friston et al., 1995; Friston et al., 2007), these statistics have been validated for the assessment of three dimensional, time varying (1D) kinematic and force vectors (Pataky, 2016a) in research settings. From a research standpoint, the development of vector-field statistics for the analysis of clinical gait can also mitigate the probability of making type I and II errors in the statistical assessment of time varying gait data (Pataky et al., 2013). The utility of vector-field statistics for the analysis of time varying gait data within clinical gait settings is also apparent. Specifically, vector-field statistics have the potential to assist in the objective analysis of these complex signals (i.e., pre- versus post- versus normative), helping to improve the inter- and intra- clinician analysis reliability of these data.

The primary aim of this communication was to compare the subjective analysis of pre- versus post- clinical gait data between two trained clinical gait experts and a vector-field statistical

method. We predict vector-field statistics will corroborate with the subjective clinical analysis of both clinical gait experts as the statistical methodology considers the within-dataset time varying variability in its entirety. A secondary aim of this communication was to conduct an exploratory analyses of the same data using a pre- versus post- 0D scalar analysis. The purpose of these analyses are for completeness, and to highlight some potential limitations associated with the 0D analysis of clinical gait data in an exploratory type setting.

2.0 Methods:

A single paediatric participant (4.4 yrs, 121 cm, 26.4 kg) classified as spastic type left hemiplegic Cerebral Palsy (GMFCS I) was the case study chosen for these analyses. A seven camera motion capture system operating at 100 Hz (Vicon MX) recorded three dimensional (3D) kinematic marker trajectories during walking gait four days prior to and four weeks following a single botulinum toxin (BoNT-A) injection to the left gastrocnemius muscle. During each testing session, 20 individual trials were recorded at the participant's self-selected walking speed.

The kinematic marker set and three dimensional lower-limb kinematic modelling procedures, which used a Calibrated Anatomical System Technique (CAST) and functional hip and knee joint axes and/or centres. Full modelling procedures have been describe previously (Besier et al., 2003). Aligning with ISB recommendations, the anatomical degrees of freedom for each joint were flexion/extension, ab/adduction and internal/external rotation (Besier et al., 2003; Ebert et al., 2013). For simplicity, a condensed clinical gait report, which contained the three dimensional kinematics of the left and right hip, knee and ankle separated into their anatomical degrees of freedom (n = 18) was used for analyses (figure 1, pane 1). All data were time normalised to 100% stride. See appendix A for full three dimensional kinematic gait report.

Three analyses were performed. First, two testers with 11 and 7 years' experience analysing paediatric cerebral palsy gait independently assessed the mean time varying joint kinematics of the participant pre- versus post- BoNT-A injection (Figure 1, pane 1). The testers were instructed to report all clinically meaningful kinematic differences within the stance and swing phase of the gait cycle. They were also asked to report when within the normalised gait cycles these differences were observed, as well as the direction of these changes. See Appendix B for written instructions provided to testers.

Second, statistical parametric mapping (SPM), specifically a Hotelling's T^2 test ($\alpha = 0.05$) were used to assess the three dimensional (i.e., 3-Component) time varying (1D) vectors of the hip, knee and ankle joint. By modelling the hip, knee and ankle as a 3-Component vector, the flexion/extension, ab/adduction, internal/external kinematic waveforms, as well as collinearities between them are all modelled statistically. If significant differences were observed, the three dimensional time varying (1D) vector was separated into its vector components, and analysed as time varying (1D) scalar waveforms. Conceptually, these analyses would be comparable to using a *post hoc* analysis when a main effect is identified with a three factor ANOVA. See appendix C for a two component time varying (1D) vector analysis.

Agreement between both testers and vector-field analysis were assessed throughout the stance and swing phase of a stride. Agreement was operationally defined as when the same pre- versus post- kinematic difference was observed, when the observed difference were in the same direction and when the timing of this difference were in alignment (≥80% of the observed difference).

Third, the discrete 0D statistical analysis of 18 independent kinematic waveforms pre- versus post- BoNT-A injection were performed. To accomplish this, the local minimum and maximum of each kinematic waveform within the stance and swing phases of the gait cycle were analysed. All 0D scalar variables were analysed using independent sample t-tests ($\alpha = 0.05$). As these analyses were exploratory in nature without any *a pirori* hypotheses, protected *post-hoc* adjustments for multiple comparisons were not made. It should be noted that pre- versus normative and post- versus normative vector-field statistical analyses can be performed. Additionally, any alpha level can be chosen for these statistical analyses of these waveform data (i.e., $\alpha = 0.05, 0.01, 0.10$). By using random field theory within the vector field statistical approach, alpha is protected for the analysis of time varying and three dimensional or n-Component vector waveforms.

3.0 Results:

The time varying (1D) vector analysis of the three dimensional (i.e., 3-Component) vectors for the left and right hip, knee and ankle were statistically different pre- versus post- BoNT-A injection (Figure 1, pane 2). The time varying (1D) scalar analysis of each joint degree of freedom, pre- versus post- BoNT-A injection (Figure 1, pane 3) revealed statistical differences

for all but two lower limb joint degrees of freedom. These include the left hip flexion/extension and right ankle plantar/dorsiflexion.

When comparing the subjective assessments of the two testers, they were in agreement between each other for 61% of the joint degrees of freedom and phases of motion assessed (Table 1). For tester 1, there was agreement with the vector-field analysis for 78% of the variables analysed. For tester 2, they were in agreement with the vector-field analysis for 53% of the variables analysed. When the subjective analyses of tester 1 and tester 2 were pooled together, they were in agreement with the vector field analysis for 83% of the time varying kinematic variables analysed. This is practically significant as clinical gait reports are generally analysed in teams with or two more clinical gait experts.

For the 0D analysis, only three of the 72 discrete variables assessed did not reported pre- versus post- statistical differences (Table 1). These included left ankle inversion/eversion and right ankle plantar/dorsiflexion during stance, and right knee internal/external rotation during swing. For 22 of the 36 gait phase and joint degree of freedom combinations analysed, both the local minimum and local maximum were significantly different.

4.0 Discussion:

Results showed that for over 80% of the lower limb kinematic variables analysed, one of the two clinical gait experts' subjective analyses of these data were in agreement with the SPM vector analyses. We feel this is a practically meaningful result as clinical gait case studies are generally analysed in teams of two or more gait experts. We acknowledge that the kinematic variables the testers did not agree upon during their analysis may not have translated to differences in their clinical interpretation(s)/recommendation(s) of the data. These results simply show vector-field statistics can provide objective, clinically meaningful information for the analysis of time varying kinematic data. We feel this is a meaningful step forward for the objective, exploratory analysis of gait data, as clinicians are provided a statistical tool from which best practice clinical decision making can be built from.

Vector-field statistics offers clinicians an objective analysis framework to work from when formulating conclusions and/or making clinical decisions from pre- versus post- versus normative clinical gait data. What is interesting to note is that both researchers, and SPM reported increases in left ankle dorsi-flexion following the BoNT-A injection, which aligns with previous research studies utilising a vector field statistical approach to assess the influence of BoNT-A as a clinical treatment for a similar same populations (Nieuwenhuys et al., 2016).

However, SPM did not identify the same differences in knee extension kinematics, which have been documented previously (Nieuwenhuys et al., 2016). In addition, for this clinical case study, SPM identified statistical difference at the hip, knee and ankle, which were not observed previously (Nieuwenhuys et al., 2016). These results highlight the importance of using an exploratory time varying analysis method like vector field statistics, as each case study is patient and treatment specific.

We appreciate that vector field statistics may be initially perceived by some researchers or clinicians as a computationally cumbersome or a time expensive analysis tool. In reality, vector field statistics simplifies the analysis of time varying data. Therein, 1D analyses of a time varying waveform can be performed in single step versus researchers attempting to pull out multiple 0D variables that best characterises the time varying behaviour of the signal. An additional, and underappreciated benefit for using vector field statistics method over a 0D statistical approach is that time does not need to be spent consciously deliberating on the rational/method(s) to protect, or not protect alpha. For example, it could be argued that for the 0D scalar analysis presented in this manuscript, alpha should have been protected for four comparisons (i.e., two maximums and two minimums). Our rational for not protecting alpha is that clinical gait analyses are exploratory in nature. This type of argument is avoided when using SPM, as random field theory and the temporal smoothness of the time varying signals are used to define and protect alpha.

As the focus of this communication was to explore vector-field statistics as a clinical gait analysis tool, future research is recommended to assess whether this statistical approach may alter or influence the clinical decision making for, and/or assessment of, interventions like orthopaedic surgery, BoNT-A treatment, casting, etc. In addition, we encourage researchers to investigate the utility of vector field statistics for the clinical assessment of joint moments, joint power and joint work pre- versus post- intervention(s).

5.0 References:

Besier T.F., Sturnieks D.L., Alderson J.A., Lloyd, D.G., Repeatability of gait data using a functional hip joint centre and a mean helical knee axis. *J Biomech.* 2003. 36(8):1159-1168.

Ebert J.R., Hambly K., Joss B., Ackland T.R., Donnelly C.J., Does an Unloader Brace Reduce Knee Loading in Normally Aligned Knees? *Clin. Orth. and Rel. Res.* 2013. 472(3):915-922.

Friston K.J., Ashburner J.T., Kiebel S. J., Nichols T. E., Penny W.D. *Statistical Parametric Mapping: The Analysis of Functional Brain Images*. Elsevier/Academic Press, Amsterdam. 2007.

Friston K., Holmes A., Worsley K., Poline J., Firth C., Frackowiak R., Statistical Parametric Maps in Functional Imaging: a general linear approach. *Human Brain Mapping*. 1995. 2(4):189-210.

Nieuwenhuys A, Papageorgiou E, Pataky T, De Laet T, Molenaers G, Desloovere K (2016). Literature Review and Comparison of Two Statistical Methods to Evaluate the Effect of Botulinum Toxin Treatment on Gait in Children with Cerebral Palsy. *PLoS One*. 31;11(3):e0152697. doi: 10.1371/journal.pone.0152697.

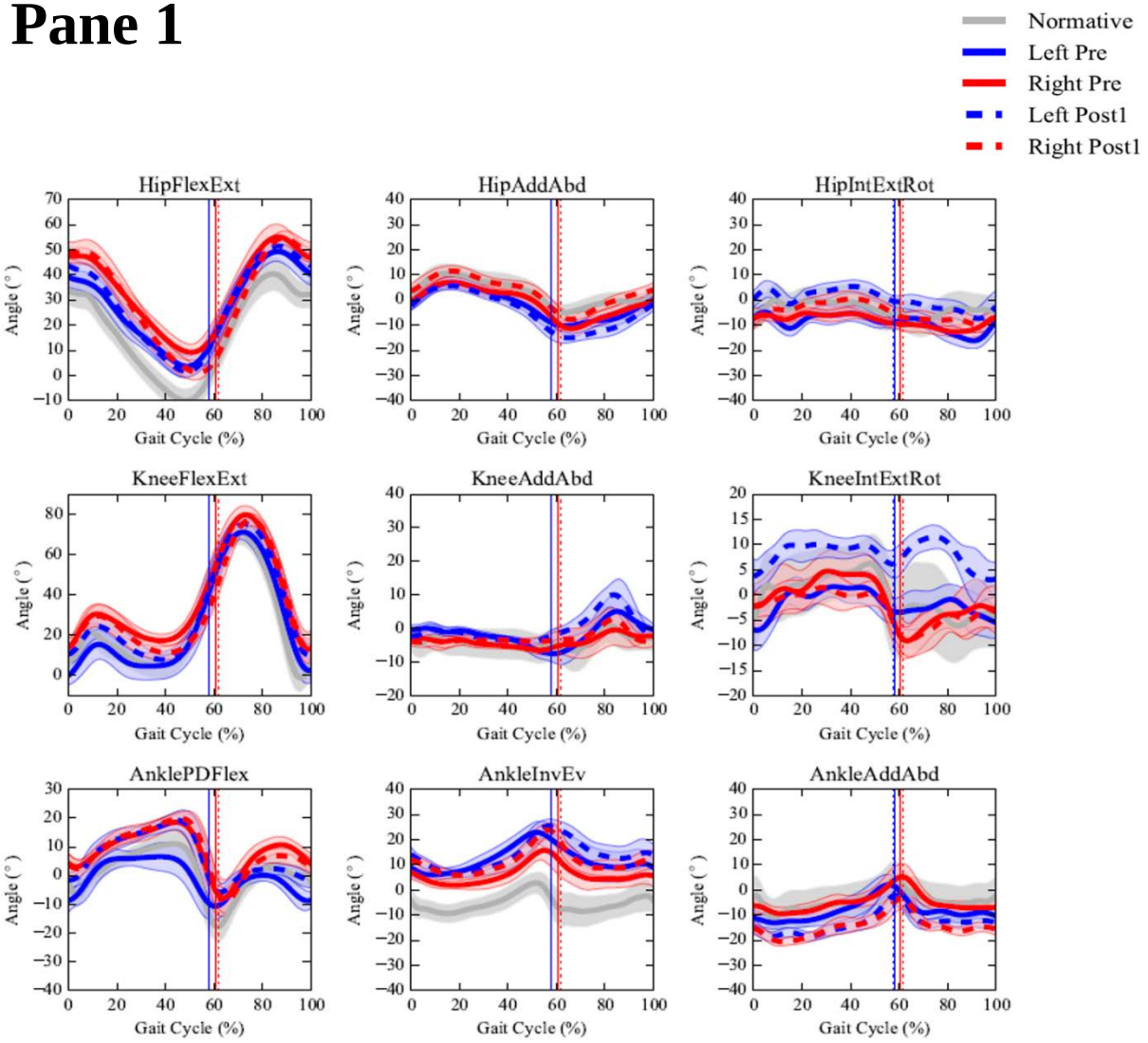
Pataky T.C., Robinson M.A., Vanrenterghem J., Vector-field statistical analysis of kinematic and force trajectories. *J Biomech*. 2013. 46(14):2394-2401.

Pataky T.C., RFT1D: Smooth one-dimensional random field upcrossing probabilities in Python. *J Statistical Software*. 2016a, [*in-press*]

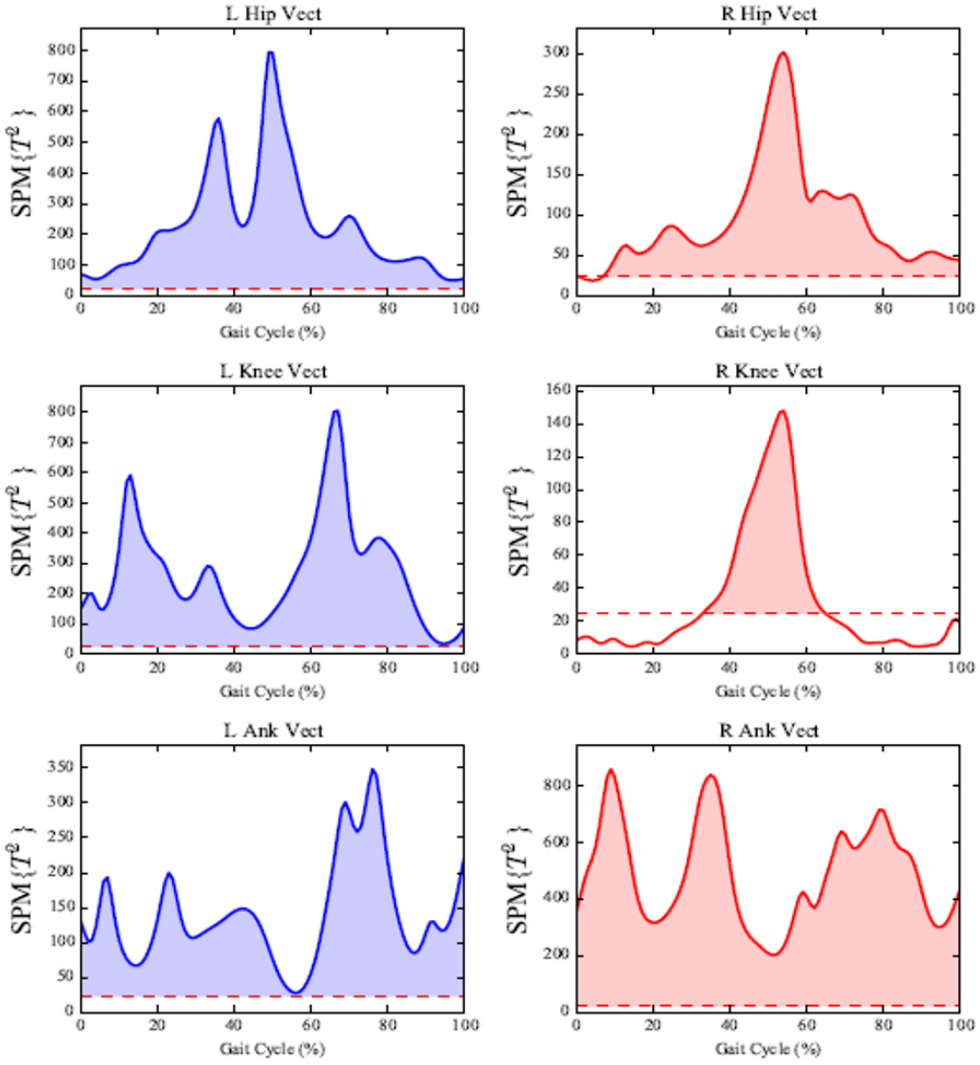
Pataky T.C., Robinson M.A., Vanrenterghem J., The probability of false positives in zero-dimensional kinematic, force and EMG trajectories. *J Biomech*. 2016b. 49:1468-1476.

Winter D. *Motor Control of Human Movement*. 3 ed. Hoboken, New Jersey: John Wiley & Sons, Inc., 2005.

Pane 1


Normative
Left Pre
Right Pre
Left Post1
Right Post1
HipFlexExt
HipAddAbd
HipIntExtRot
KneeFlexExt
KneeAddAbd
KneeIntExtRot
AnklePDFlex
AnkleInvEv
AnkleAddAbd
Angle (°)
Gait Cycle (%)

Pane 2


L Hip Vect
R Hip Vect
L Knee Vect
R Knee Vect
L Ank Vect
R Ank Vect
SPM{T²}
Gait Cycle (%)

Pane 3

Left Limb (treatment)

Right Limb

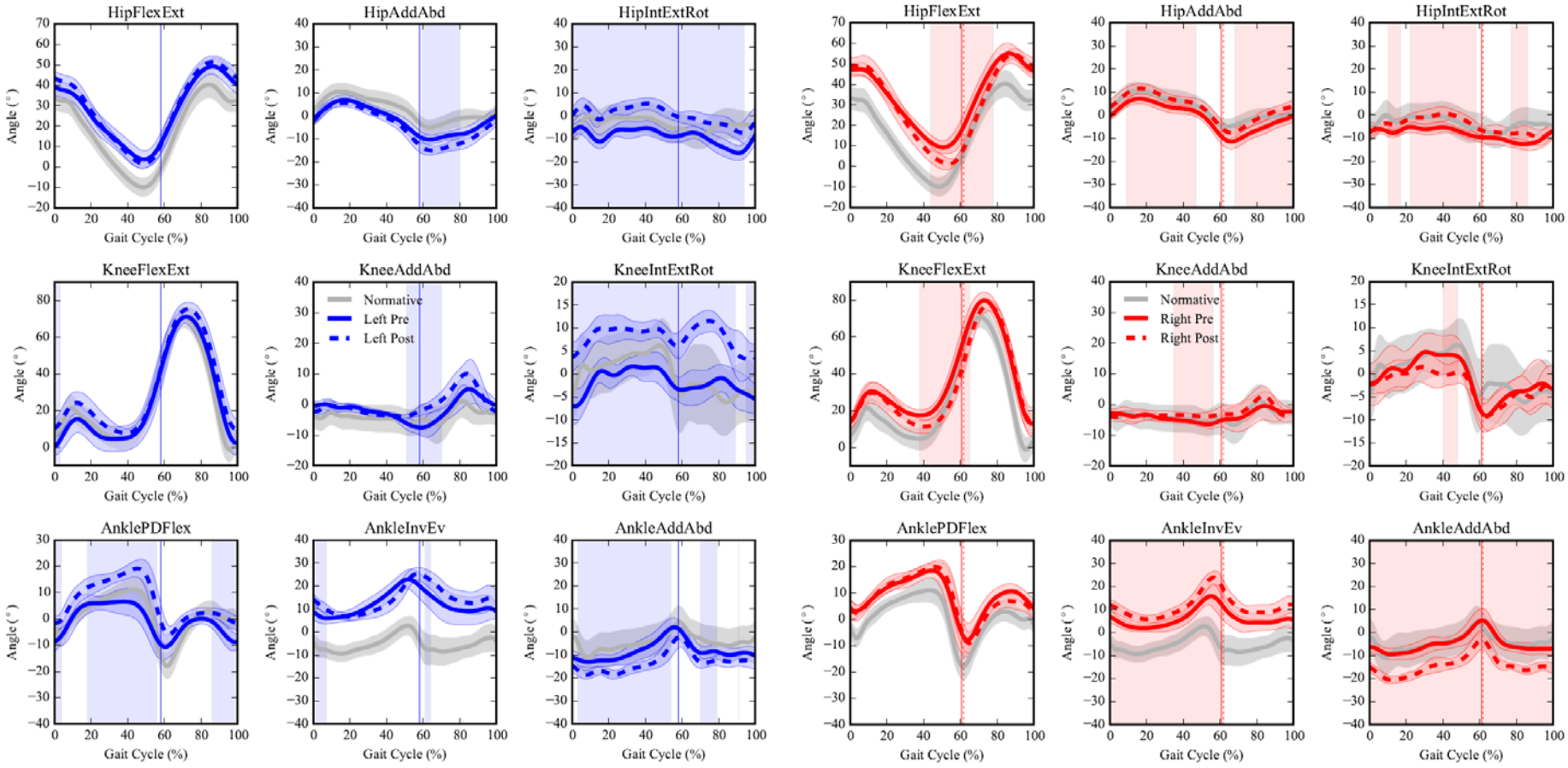


Figure 1: Pane 1 represents the time varying kinematics of the ankle, knee and hip joint separated into their anatomical degrees of freedom (flexion/extension, ab/adduction and internal/external rotation) pre- versus post- BoNT-A injection. Positive values for the hip, knee and ankle represent flexion or dorsiflexion (ankle), adduction or inversion (ankle) and internal rotation or adduction (ankle). Pane 2 represents the three component 1D vector analysis of the hip, knee and ankle pre- versus post- BoNT-A injection. In pane 2, where the T^2-statistic (blue or red line) is greater than the critical T^2-threshold (red dotted line)($\alpha = 0.05$), a significant pre- versus post- difference related to the BoNT-A injection is observed. It should be noted that the t-statistic can be interpreted as an effect size. The further the T^2-statistic deviates from the critical T^2-threshold defined by the experimental alpha level, the larger the relative effect. Pane 3 represents the scalar 1D analysis of the ankle, knee and hip joint separated into their anatomical degrees of freedom pre- versus post- BoNT-A injection. For simplicity, regions of statistical difference ($\alpha = 0.05$) are highlighted in red or blue. The direction of the difference is interpreted from the pre- versus post- kinematic data presented within the shaded regions. For interested readers, the *t*-statistic and critical *t*-threshold for the scalar 1D analysis of the ankle, knee and hip joint are presented in Figure S4 of the supplementary materials.

Table 1: Agreement between both testers and SPM through the stance and swing phase of the participant's stride. Agreement between both testers and SPM was assessed through the stance and swing phase of the participant's stride. Agreement was operationally defined as when the same pre- versus post- kinematic difference was observed, when the observed difference was in the same direction and when the timing of this difference was in alignment (≥80% of the observed difference). In addition, for each degree of freedom, local pre- versus post- 0D difference (local minima and maxima) during the stance and swing phase of a single stride.

Joint DoF (1D or 0D)	**Stance Phase Observation**	**Swing Phase Observation**
L Hip Flex/Ext (1D)	[a] Tester 1: ↑ flexion 0-20% [b] Tester 2: ↓ flexion 45-55% [c] SPM: ↔	[a] Tester 1: ↔ [a] Tester 2: ↔ [a] SPM: ↔
L Hip Flex/Ext (0D)	Max ↑:39.3(4.0)/43.8(3.4); ***p* = 0.001** Min ↔: 3.0(4.2) /1.2(2.5); *p* = 0.091	Max ↑: 49.7(3.9) /51.9(3.1); ***p* = 0.026** Min ↔: 9.3(6.5) /7.2(4.5); *p* = 0.241
L Hip Add/Abd (1D)	[a] Tester 1: ↔ [b] Tester 2: ↑ abduction 45-60% [a] SPM: ↔	[a] Tester 1: ↑ abduction 60-100% [a] Tester 2: ↑ abduction 60-100% [a] SPM: ↑ abduction 60-80%
L Hip Add/Abd (0D)	Max ↓: 7.2(2.0) /5.9 (1.5); ***p* = 0.026** Min ↓:-7.8(3.1)/-10.3(3.6); ***p* = 0.028**	Max ↔: 0.2(3.0) /-1.4(2.8); *p* = 0.093 Min ↓: -11.4(1.6) /-15.6(2.1); ***p* <0.001**
L Hip Int/Ext Rot (1D)	[a] Tester 1: ↑ int. rot 0-60% [a] Tester 2: ↑ int. rot 0-60% [a] SPM: ↑ int. rot 0-60%	[a] Tester 1: ↓ ext. rot 60-100% [a] Tester 2: ↓ ext. rot 60-100% [a] SPM: ↓ ext. rot 60-95%
L Hip Int/Ext Rot (0D)	Max ↑: -2.2 /(2.3) /7.2(2.1); ***p* <0.001** Min ↑: -12.7(2.4) /-3.6(2.1); ***p* <0.001**	Max ↑: -5.3(2.3) /3.0(2.7); ***p* <0.001** Min ↑: -17.3(2.9) /-9.6(3.8); ***p* <0.001**
L Knee Flex/Ext (1D)	[a] Tester 1: ↑ flexion 0-40% [b] Tester 2: ↑ flexion 0-5% [b] SPM: ↑ flexion 0-5%	[a] Tester 1: ↑ flexion 95-100% [b] Tester 2: ↑ flexion 70-80% [c] SPM: ↔
L Knee Flex/Ext (0D)	Max ↔: 34.9(13.2)/33.3(9.5); *p*= 0.679 Min ↑: -1.4(4.1) /6.9(2.0); ***p* <0.001**	Max ↑: 72.6(3.1) /76.1(3.9); ***p* = 0.005** Min ↑: 1.7(5.8) /9.1(5.9); ***p* <0.001**
L Knee Add/Abd (1D)	[a] Tester 1: ↑ adduction 50-60% [b] Tester 2: ↔ [a] SPM: ↑ adduction 50-60%	[a] Tester 1: ↑ adduction 60-90% [b] Tester 2: ↔ [a] SPM: ↑ adduction 60-70%
L Knee Add/Abd (0D)	Max ↓ : 1.0(1.4) /0.6(1.5); ***p* = 0.003** Min ↑: -7.3(1.8) /-4.1(0.6); ***p* <0.001**	Max ↑: 6.5(4.2) /11.7(4.2); ***p* = 0.002** Min ↑: -8.4(3.0) /-3.5(1.0); ***p* <0.001**
L Knee Int/Ext Rot (1D)	[a] Tester 1: ↑ int. rot 0-60% [a] Tester 2: ↑ int. rot 0-60% [a] SPM: ↑ int. rot 0-60%	[a] Tester 1: ↑ int. rot 60-100% [a] Tester 2: ↑ int. rot 60-100% [a] SPM: ↑ int. rot 60-85;95-100%
L Knee Int/Ext Rot (0D)	Max ↑: 3.4(1.7) /12.2(1.7); ***p* <0.001** Min ↑: -8.3(3.5) /2.2(2.4); ***p* <0.001**	Max ↑: 1.3(2.7) /12.3(1.9); ***p* <0.001** Min ↑: -7.8(1.9) /0.7(3.7); ***p* <0.001**
L Ankle P/D flexion (1D)	[a] Tester 1: ↑ D. Flexion 0-60% [a] Tester 2: ↑ D. Flexion 10-40;45-55% [a] SPM: ↑ D. Flexion 0-5%;20-55%	[a] Tester 1: ↑ D. Flexion 80-100% [a] Tester 2: ↑ D. Flexion 90-100% [a] SPM: ↑ D. Flexion 80-100%

L Ankle P/D flexion (0D)	Max ↑: 9.4(2.9) /20.0(2.8); ***p* <0.001** Min ↑:-11.1(2.7) /-3.6(2.7); ***p* <0.001**	Max ↑: 1.1(4.1) /7.2(5.8); ***p* = 0.001** Min ↑: -12.6(4.1) /-7.2(3.3); ***p* <0.001**
L Ankle Inv/Ever (1D)	[a] Tester 1: ↑ inversion 0-20% [b] Tester 2: ↔ [a] SPM:↑ inversion 0-10%	[a] Tester 1: ↑ inversion 60-100% [b] Tester 2: ↔ [c] SPM: ↑ inversion at 60%
L Ankle Inv/Ever (0D)	Max ↔:23.6(4.4)/24.8(2.6); $p = 0.259$ Min ↔: 5.5(2.4) /6.2(1.6); $p = 0.312$	Max ↑: 20.5(5.3) /25.9(2.8); ***p* = 0.001** Min ↑: 7.0(4.6) /11.5(4.0); ***p* = 0.002**
L Ankle Add/Abd (1D)	[a] Tester 1: ↑ abduction 5-60%; [a] Tester 2:↑ abduction 0-60%; [a] SPM:↑ abduction 0-60%;	[a,b] Tester 1: ↑ abduction 70-100% [a] Tester 2: ↑ abduction 60-100% [b] SPM: ↑ abduction 70-80%
L Ankle Add/Abd (0D)	Max ↓: 2.1(4.5) /-4.7(5.5); ***p* <0.001** Min ↓:-14.3(2.4)/-19.7(1.9);***p* <0.001**	Max ↓: 2.4(4.5) / -1.2(4.4); ***p* = 0.013** Min ↓:-11.6(3.1) /-14.9(1.9); ***p* = 0.001**
R Hip Flex/Ext (1D)	[a] Tester 1: ↓ flexion 30-60% [a] Tester 2: ↓ flexion 45-60% [a] SPM: ↓ flexion 40-60%	[a] Tester 1: ↓ flexion 60-85% [b] Tester 2: ↔ [a] SPM: ↓ flexion 60-80%
R Hip Flex/Ext (0D)	Max ↔: 48.1(3.3) /49.9(4.6);$p = 0.169$ Min ↓: 8.7(3.0) /0.8(2.7); ***p* <0.001**	Max ↔: 55.4(5.0) /55.0(2.7); $p = 0.623$ Min ↓:15.7(7.8) /6.4(5.1); ***p* <0.001**
R Hip Add/Abd (1D)	[a] Tester 1: ↑ adduction 0-60% [b] Tester 2: ↔ [a] SPM: ↑ adduction 5-45%	[a] Tester 1: ↓ abduction 60-75%; ↑ adduction 75-100% [b] Tester 2: ↔ [a] SPM: ↓ abduction 65-75%; ↑ adduction 75-100%
R Hip Add/Abd (0D)	Max ↑: 7.4(1.9)/ 11.9(2.2); ***p* <0.001** Min ↑: -6.4(4.0) /-3.8(3.3); $p = 0.071$	Max ↑: 0.2(2.6) /4.3(2.4); ***p* <0.001** Min ↑:: -12.0(3.0) /-8.0(2.3); ***p* <0.001**
R Hip Int/Ext Rot (1D)	[a] Tester 1: ↓ ext. rot. 0-60% [b] Tester 2: ↔ [a] SPM: ↓ ext. rot. 10-18;22-60%	[a] Tester 1: ↓ ext. rot. 60-90% [b] Tester 2: ↔ [a] SPM: ↓ ext. rot. 75-85%
R Hip Int/Ext Rot (0D)	Max ↑: -3.0(1.9) /1.9(2.4); ***p* <0.001** Min ↑:-10.9(1.9) /-8.5(1.7); ***p* <0.001**	Max ↑: -5.8(2.8) /-3.1(1.7); ***p* <0.001** Min ↑: -14.4(1.8) /-11.6(2.3); ***p* <0.001**
R Knee Flex/Ext (1D)	[a] Tester 1: ↓ flexion 20-60% [a] Tester 2: ↓ flexion 40-50% [a] SPM: ↓ flexion 40-60%	[a] Tester 1: ↓ flexion 60-85% [b] Tester 2: ↔ [a] SPM:↓ flexion 60-65%
R Knee Flex/Ext (0D)	Max ↓:46.0(13.2)/39.3(8.1);***p* <0.001** Min ↓:12.5(2.8) /9.6(3.2); ***p* <0.001**	Max ↓: 80.4(4.3) /77.8(3.2); ***p* <0.001** Min ↑: 12.2(5.6) /13.2(7.8); ***p* <0.001**
R Knee Add/Abd (1D)	[a] Tester 1: ↔ [a] Tester 2: ↔ [b] SPM: ↑ adduction 35-60%	[a] Tester 1: ↔ [a] Tester 2: ↔ [a] SPM: ↔
R Knee Add/Abd (0D)	Max ↔: -1.7(1.6) /-2.0(1.3); $p = 0.536$ Min ↑: -6.9(1.5) /-5.4(1.6); ***p* <0.001**	Max ↔: 1.2(3.5) /3.4(3.1); $p = 0.057$ Min ↑: -7.2(2.7) /-5.1(2.6); ***p* = 0.037**
R Knee Int/Ext Rot (1D)	[a] Tester 1: ↔ [a] Tester 2: ↔ [b] SPM: ↓ int. rot. 40-50%	[a] Tester 1: ↔ [a] Tester 2: ↔ [a] SPM: ↔
R Knee Int/Ext Rot (0D)	Max ↓: 6.2(3.9)/ 3.4(2.8); ***p* = 0.001** Min ↔: -6.6(4.5) /-7.0(2.5); $p = 0.707$	Max ↔: 0.3(3.1) /0.1(2.6); $p = 0.798$ Min ↔:-11.1(3.3) /-10.4(2.5); $p = 0.488$
R Ankle P/D flex (1D)	[a] Tester 1: ↔ [a] Tester 2: ↔	[a] Tester 1: ↓ D. flexion 70-100% [b] Tester 2: ↔

	[a] SPM: ↔	[b] SPM: ↔
R Ankle P/D flex (0D)	Max ↔:19.4(2.6)/20.6(2.1); p = 0.163 Min ↔: -2.8(6.0) /-3.8(4.9); p = 0.418	Max ↓: 11.9(3.7) /9.0(3.4); ***p* = 0.011** Min ↔: -9.0(6.3) /-10.1(3.7); p = 0.468
R Ankle Inv/Evr (1D)	[a] Tester 1: ↑ inversion 0-60% [a] Tester 2: ↑ inversion 0-60% [a] SPM: ↑ inversion 0-60%	[a] Tester 1: ↑ inversion 60-100% [a] Tester 2: ↑ inversion 60-100% [b] SPM: ↑ inversion 60-65%
R Ankle Inv/Evr (0D)	Max ↑:16.7(4.2) /24.6(2.4); ***p* <0.001** Min ↑: 1.1(1.5) / 5.5(1.7); ***p* <0.001**	Max ↑: 13.9(5.5) /21.0(4.8); ***p* <0.001** Min ↑: 2.3(3.3) /7.7(3.0); ***p* <0.001**
R Ankle Add/Abd (1D)	[a] Tester 1: ↑ abduction 0-60% [a] Tester 2: ↑ abduction 0-60% [a] SPM: ↑ abduction 0-60%	[a] Tester 1: ↑ abduction 60-100% [a] Tester 2: ↑ abduction 60-100% [a] SPM:↑ abduction 60-100%
R Ankle Add/Abd (0D)	Max ↓: 3.7(4.8) /-4.3(4.7); ***p* <0.001** Min ↓:-10.5(2.5)/-21.2(1.5);***p* <0.001**	Max ↓: 5.6(5.3) /-2.7(4.2); ***p* <0.001** Min ↓: -8.5(2.2) /-17.5(1.6); ***p* <0.001**

1D analyses

% indicates percentage of stride where difference were observed

↑ - Increase | ↓ - Decrease | ↔ - No-change

Letters a, b, c indicates agreement between assessments (testers and SPM scalar statistic). There is agreement if they possess the same letter and disagreement if they possess different letters.

0D analyses

Ho: Maxima Pre = Maxima Post

Ho: Minima Pre = Minima Post

↑ - *Increase/more*| ↓ - *Decrease/less* | ↔ - *No-change*

Appendix A: Full gait analysis. Normative data band used for reference, however vector field statistics can be used to compare it to the pre- versus and/or post- kinematic waveform data.

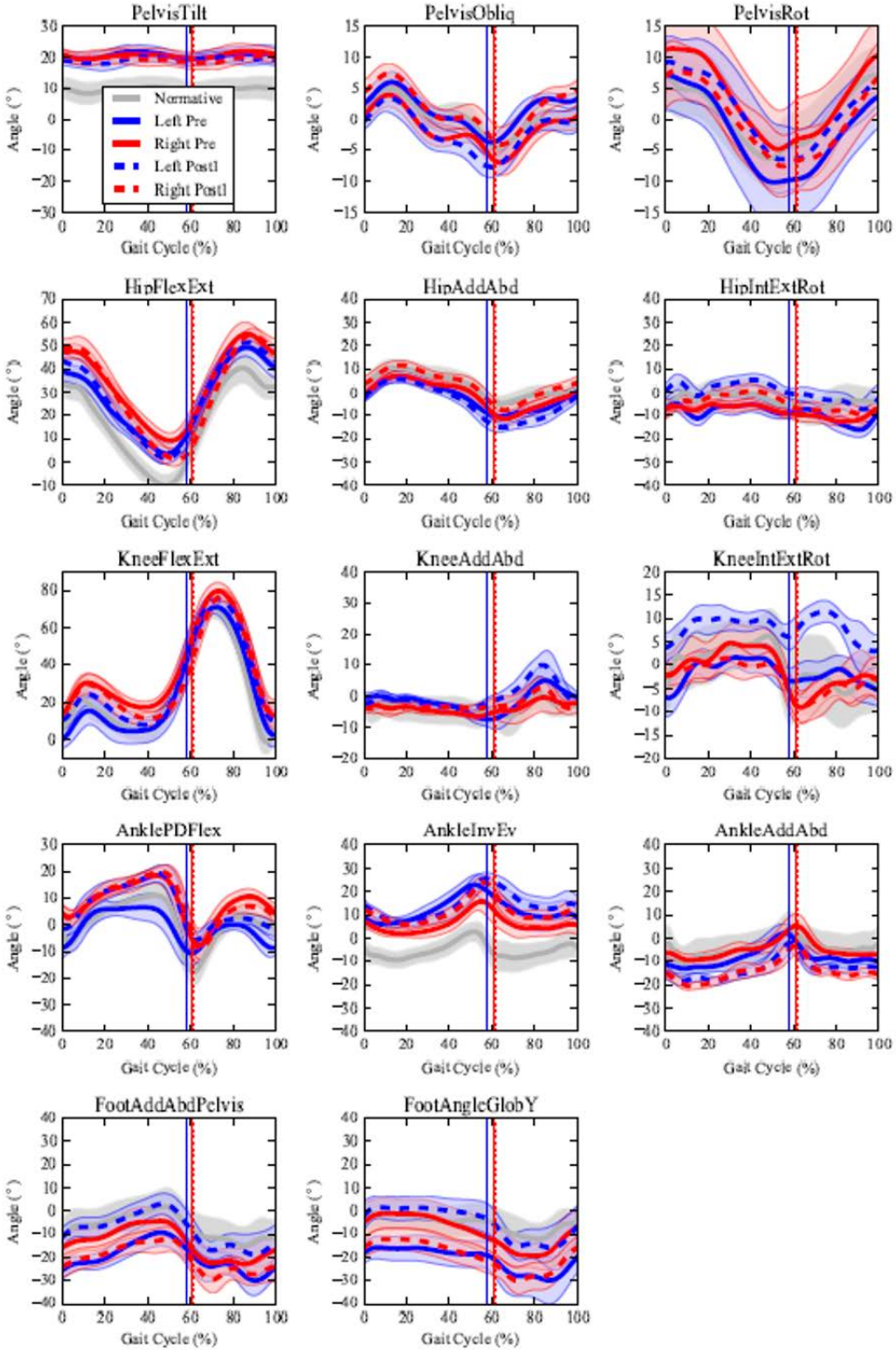


Figure S1: An example of a full kinematic gait assessment. The time varying kinematics of the pelvis segment, hip joint, knee joint, ankle joint and foot segment pre- versus post- BoNT-A injection are presented. The pelvis segment, hip joint, knee joint, ankle joint were separated

into their anatomical degrees of freedom (flexion/extension or tilt, ab/adduction or obliquity internal/external rotation). Positive values for the pelvis, hip, knee and ankle represent flexion or dorsiflexion (ankle) or anterior tilt (pelvis), adduction or inversion (ankle) or medial obliquity (pelvis) and internal rotation or adduction (ankle). A positive value for the foot segment relative to the global coordinate system of pelvis segment or global coordinate system of the laboratory is internal rotation or adduction.

Appendix B: Written instructions to clinical gait experts.

Thank you for participating in this study. Using your experience as a clinical gait expert, we would like you to provide your clinical interpretation of the following case study.

Case Study

Patient: 4.4 yo male (121 cm, 26.4 kg) with spastic left hemiplegia (GMFCS I). Patient has no history of orthopaedic surgery and was toxin naïve at time of pre- versusintervention assessment.

Intervention: Botulinum toxin (BoNT-A) injection to the left gastrocnemius muscle.

Testing environment: Gait laboratory

Procedure: The patient was asked to attend two testing sessions. Four days prior to and four weeks following the BoNT-A intervention. During the testing sessions, the patient was asked to walk at their self-selected walking speed along a 20 m walkway. Three-dimensional (3D) motion capture data was recorded from 20 individual trials during each testing session.

Analyses: The time varying 3D joint kinematics of the left and right hip, knee and ankle were calculated and normalised to a single stride for each of the 20 gait trials pre- versus post BoNT-A injection. Heel-strike and toe-off during the stance phase was defined as when the vertical ground reaction force vector was >10 N.

Instruction

From the clinical gait report presented in figure 1, we ask that you conduct your analyses within the stance and swing phase of the gait cycle. We ask you complete your clinical gait analyses as a pre- versus post BoNT-A intervention assessment. The normative data bands have been provided for reference only [comment relative to normative data is not required]. If you observe clinically meaningful kinematic differences pre- versus post BoNT-A intervention in any of the gait waveforms provided, we ask that you report the direction and timing of these observed differences within the table provided (table 1). Once completed, please return table 1 to our independent researcher.

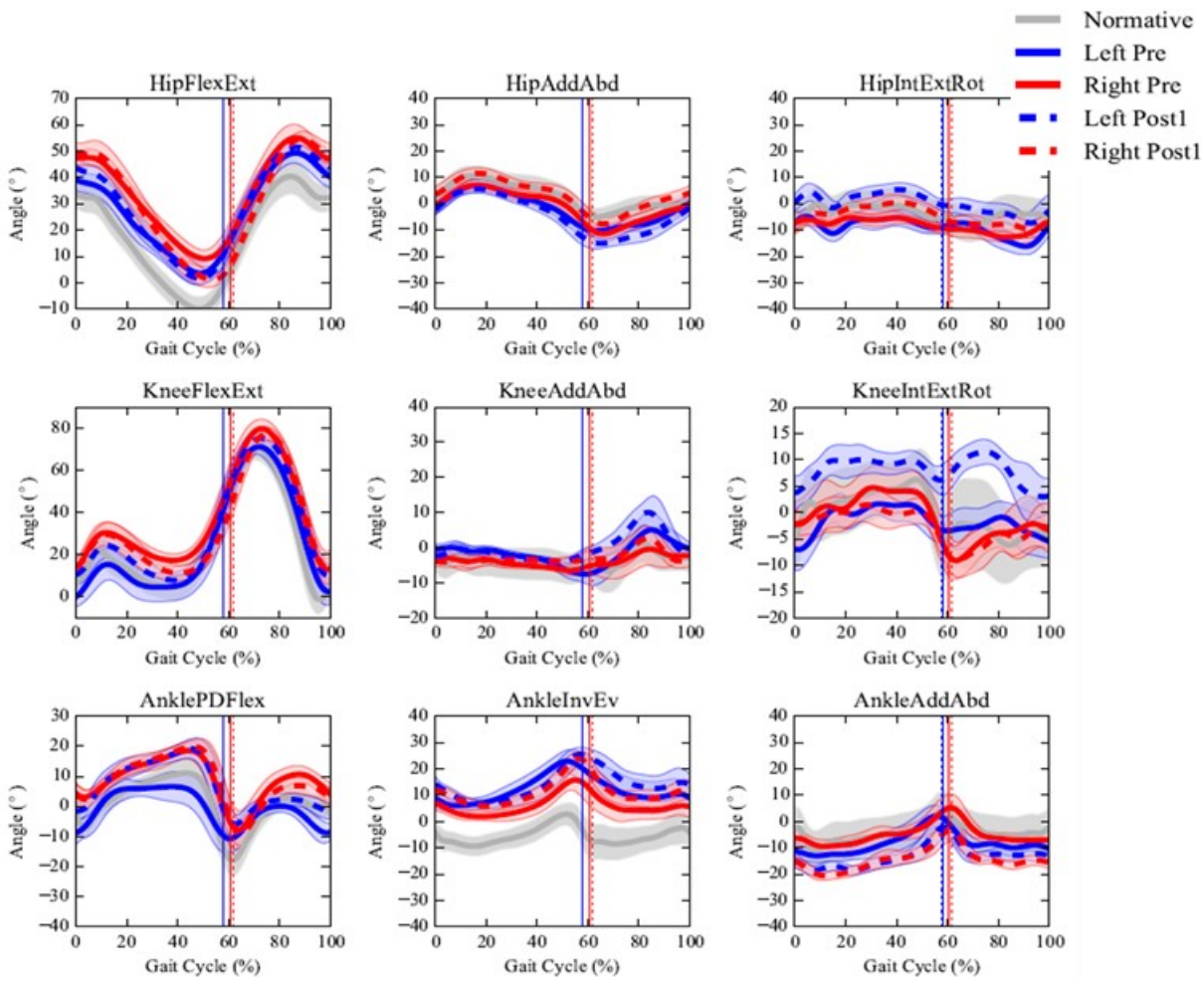


Figure S2: 3D joint kinematics of the left (blue) and right (right) hip, knee and ankle pre- versus post BoNT-A injection. Heel-strike (0% stride) and toe-off (red and blue vertical lines) are defined within the figure. The normative data bands in grey are supplied for reference. Positive values for the hip, knee and ankle represent flexion or dorsiflexion (ankle), adduction or inversion (ankle) and internal rotation or adduction (ankle).

Table S1: Clinical gait reporting table. Please provide any clinically meaningful kinematic differences pre- versus post BoNT-A intervention (*see figure S2 above*). If any pre- versus post differences are observed, please report the direction and within the table provided.

Name of clinical gait expert:		
How many years have you been conducting clinical gait assessments?:		
Are you trained as a Medical Doctor, PhD, PhD & MD or other?:		
Joint DoF	Stance Phase Observation	Swing Phase Observation
L Hip Flex/Ext		
L Hip Add/Abd		
L Hip Int/Ext Rot		
L Knee Flex/Ext		
L Knee Add/Abd		
L Knee Int/Ext Rot		

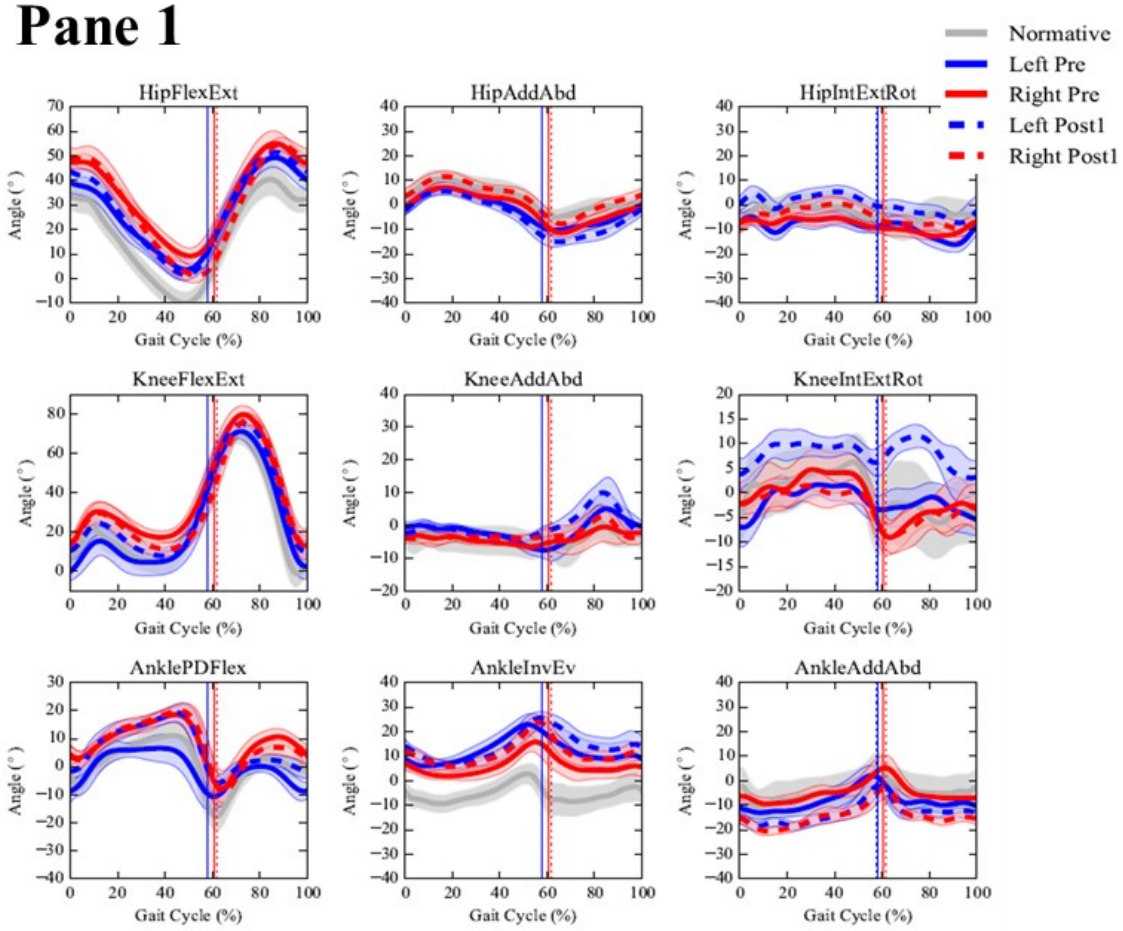
L Ankle P/D Flex		
L Ankle Inv/Ev		
L Ankle Add/Abd		
R Hip Flex/Ext		
R Hip Add/Abd		
R Hip Int/Ext Rot		
R Knee Flex/Ext		
R Knee Add/Abd		
R Knee Int/Ext Rot		
R Ankle P/D Flex		
R Ankle Inv/Ev		

R Ankle Add/Abd		

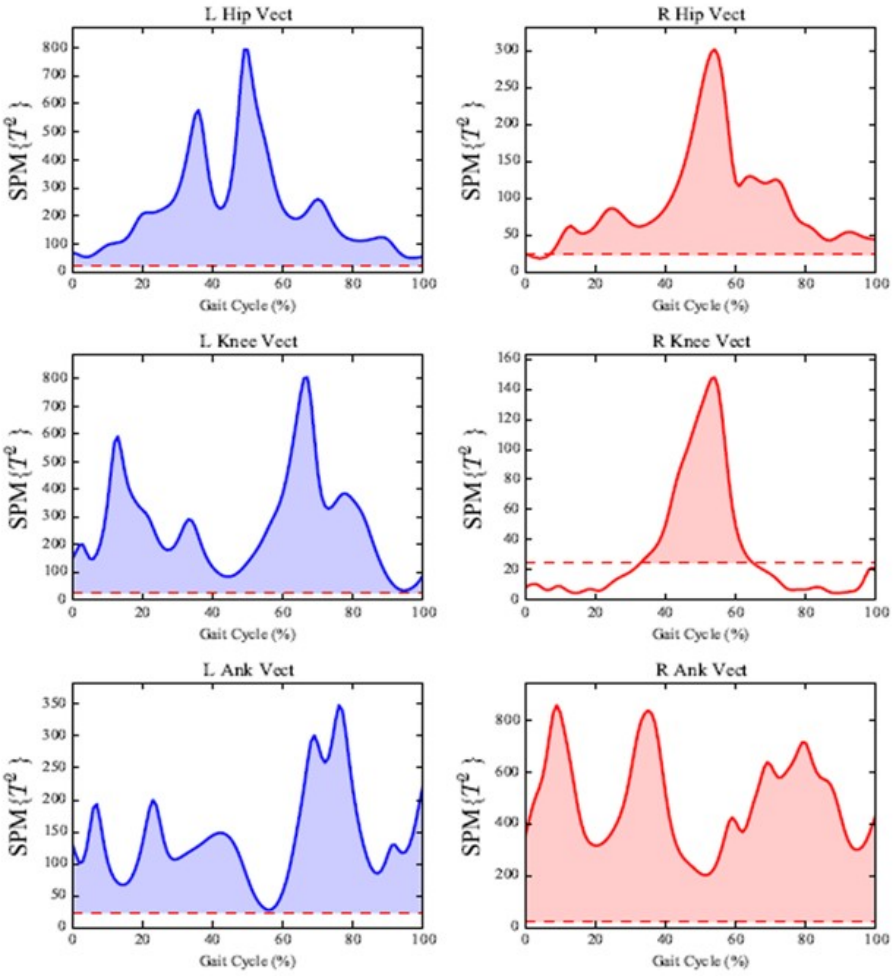
Appendix C: Three and 2-Component time varying vector analyses with T^2-statistic and critical T^2-threshold presented.

For the assessment of time varying lower limb kinematics, the authors acknowledged a 2-Component vector analysis may not be as useful as the 3-Component vector analysis or the 1-Component scalar analyses, which is why these data appear as supplementary materials. We did feel it important to show the reader that vector components can be modelled as 1, 2, 3 and n-Component vectors, which is extremely important for the kinetic analysis of clinical gait populations. Specifically, these would be useful for the analysis of knee osteoarthritis and anterior cruciate ligament populations, which require knee loads to be analysed as combined knee loading vectors. The 2-component vectors for the knee osteoarthritis would be frontal (i.e., extension) and sagittal (i.e., adduction) plane knee moments. For anterior cruciate ligament populations, transverse (i.e., internal rotation) and frontal (i.e., abduction) moments would be of interest. Researchers and clinician can also use 3, 2 and 1 component analyses as a pseudo post-hoc time varying vector test where they can isolate the vector components (n = 2) or scalar component (n = 1) that explains a three component vector (n = 3) effect.

Pane 1


Normative
Left Pre
Right Pre
Left Post1
Right Post1
HipFlexExt
HipAddAbd
HipIntExtRot
KneeFlexExt
KneeAddAbd
KneeIntExtRot
AnklePDFlex
AnkleInvEv
AnkleAddAbd
Angle (°)
Gait Cycle (%)

Pane 2



Pane 3

Left Limb (treatment) *Right Limb*

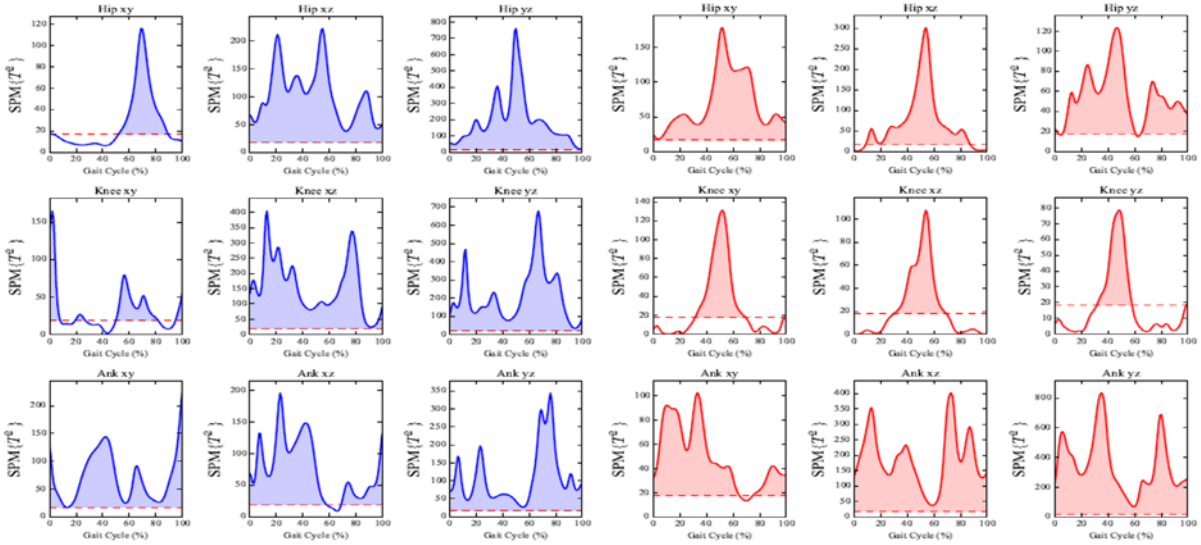


Figure S3: Pane 1 represents the time varying kinematics of the ankle, knee and hip joint separated into their anatomical degrees of freedom (flexion/extension, ab/adduction and internal/external rotation) pre- versus post- BoNT-A injection. Positive values for the hip, knee and ankle represent flexion or dorsiflexion (ankle), adduction or inversion (ankle) and internal rotation or adduction (ankle). Pane 2 represents the 3-Component time varying vector analysis of the hip, knee and ankle pre- versus post- BoNT-A injection. Pane 3 represent the 2-Component time varying vector analyses of the ankle, knee and hip joint. For each joint the vectors between the flexion/extension and internal/external rotation components (XY), flexion/extension and ab/adduction components (XZ), and ab/adduction and internal/external rotation (YZ) components are presented. For both the 3-Component time varying vector (middle pane) and 2-Component time varying vector analyses (bottom panes), where the T^2-statistic (blue or red line) is greater than the critical T^2-threshold (red dotted line)($\alpha = 0.05$), a significant kinematic difference pre- versus post- BoNT-A injection is observed.

Appendix D: *t*-statistic and critical *t*-thresholds for the scalar 1D SPM analysis of the ankle, knee and hip joints.

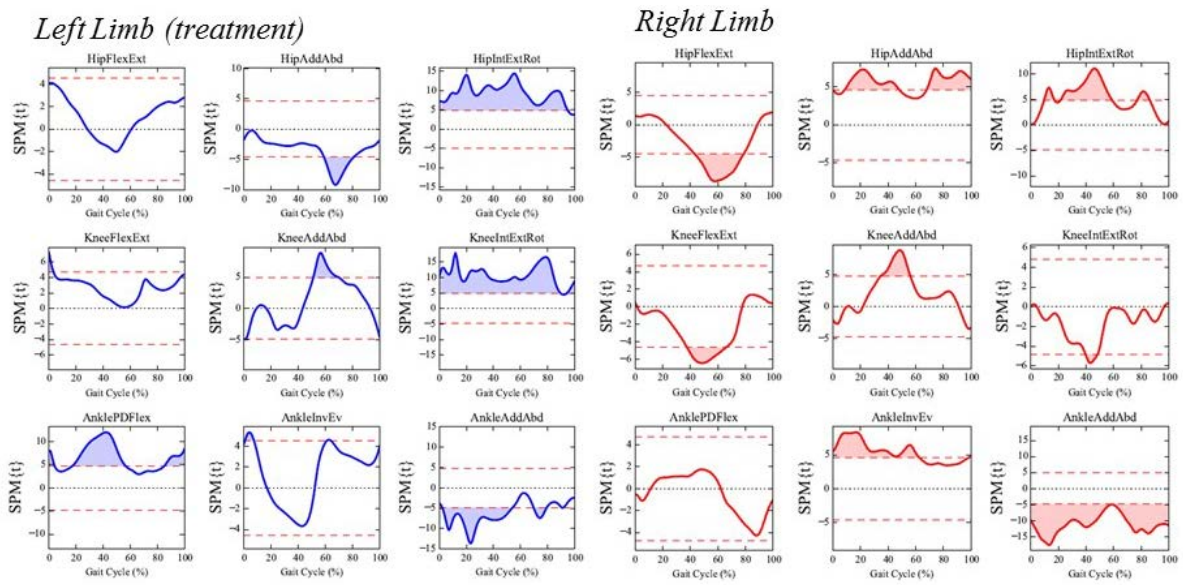


Figure S4: Depiction of the *t*-statistic and critical *t*-threshold for the scalar 1D SPM analysis of the ankle, knee and hip joint pre- versus post- BoNT-A injection. The joints are separated into their anatomical degrees of freedom (flexion/extension, ab/adduction and internal/external rotation). Positive values for the hip, knee and ankle represent pre- versus post- kinematic changes towards flexion or dorsiflexion (ankle), adduction or inversion (ankle) and internal rotation or adduction (ankle).

.