# A biomechanical comparison of powered robotic exoskeleton gait with normal and slow walking: An investigation with able-bodied individuals

Stephen Clive Hayes MSc[a], Matthew White MSc[b], Hollie Samantha Forbes White PhD[c], Natalie Vanicek PhD[a]

[a]University of Hull, School of Life Sciences, Hull, United Kingdom
[b]PhysioFunction Ltd., Chris Moody Centre, Moulten College, Moulton, United Kingdom
[c]University of Warwick, Warwick Medical School, Warwick, United Kingdom

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|---|---|
| Stephen Clive Hayes | S.Hayes@hull.ac.uk ORCID iD 0000-0003-0767-3657 |
| Matthew White | m.white@physiofunction.co.uk |
| Hollie Samantha Forbes White | Hollie.White@warwick.ac.uk |
| Natalie Vanicek | N.Vanicek@hull.ac.uk ORCID iD 0000-0002-9602-3172 |

Corresponding author
Professor Natalie Vanicek

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*Background*

Overground lower-limb robotic exoskeletons are assistive devices used to facilitate ambulation and gait rehabilitation. Our understanding of how closely they resemble comfortable and slow walking is limited. This information is important to maximise the effects of gait rehabilitation. The aim was to compare the 3D gait parameters of able-bodied individuals walking with and without an exoskeleton at two speeds (self-selected comfortable vs. slow, speed-matched to the exoskeleton) to understand how the user's body moved within the device.

*Methods*

Eight healthy, able-bodied individuals walked along a 12-metre walkway with and without the exoskeleton. Three-dimensional whole-body kinematics inside the device were captured. Temporal-spatial parameters and sagittal joint kinematics were determined for normal and exoskeleton walking. One-way repeated measures ANOVAs and statistical parametric mapping were used to compare the three walking conditions ($P<0.05$).

*Findings*

The walking speeds of the slow (0.44[0.03] m/s) and exoskeleton (0.41[0.03] m/s) conditions were significantly slower than the comfortable walking speed (1.54[0.07] m/s). However, time in swing was significantly greater ($P<0.001$, $d=-3.64$) and double support was correspondingly lower ($P<0.001$, $d=3.72$) during exoskeleton gait than slow walking, more closely resembling comfortable speed walking. Ankle and knee angles were significantly reduced in the slow and exoskeleton conditions. Angles were also significantly different for the upper body.

*Interpretation*

Although the slow condition was speed-matched to exoskeleton gait, the stance:swing ratio of exoskeleton stepping more closely resembled comfortable gait than slow gait. The altered upper body kinematics suggested that overground exoskeletons may provide a training environment that would also benefit balance training.

## *1. Introduction*

Lower-limb robotic exoskeletons (LEXOs) are wearable robots that provide external support to facilitate bipedal locomotion. Using motors, they assist the movement of a user's limbs through pre-defined joint ranges of motion (RoM). LEXO devices are intended to facilitate gait training/rehabilitation and upright mobility for those with limited or no independent walking capacity (Louie et al., 2015). Although LEXOs are designed and programmed to replicate normal walking patterns, the methods used to affix the devices to the user's body (typically hook and loop fabric) allow a degree of flexibility and movement within the system. Consequently, the user's kinematics may not expressly reproduce those of the device.

Numerous LEXOs are available, and several studies have compared overground LEXOs to able-bodied gait (Fineberg et al., 2013; Arazpour et al., 2014; Ramanujam et al*.,* 2017). Peak vertical ground reaction forces (vGRFs), between the LEXO gait of spinal cord injured (SCI) individuals and stereotypical able-bodied gait, have been reported as similar in magnitude when no external support was required from a therapist, even in light of the significantly faster walking speed of the able-bodied individuals (Fineberg et al., 2013). However, Arazpour et al. (2014) demonstrated that the temporal-spatial and RoM characteristics of SCI and able-bodied individuals using a LEXO were significantly reduced compared with normal walking. Although Ramanujam et al. (2017) and Arazpour et al. (2014) concurred regarding temporal-spatial characteristics, the two studies differed with regards to their kinematic findings. Arazpour et al. (2014) tracked the motion of the LEXO, but not the user inside the device. Ramanujam et al. (2017) noted that the SCI RoM was not significantly different from able-bodied LEXO walking, and their kinematic data were representative of the user inside the device.

Most likely due to the challenges associated with marker occlusion and placement restrictions, only three studies have been identified that have investigated the user's kinematics rather than those of the LEXO exclusively (Ramanujam et al., 2017, Hidler et al., 2008 and Knaepen et al., 2014). Two of these studies assessed the kinematics of the human-robot interaction. An active marker system was used to investigate able-bodied movement inside the treadmill-based Lokomat® system (Hocoma AG, Volketswil, Switzerland). The findings revealed significant differences between the kinematics of the individual and the device, and revealed step-to-step variability of the body independent of the Lokomat's® prescriptive pattern (Hidler et al., 2008). Knaepen et al. (2014) evaluated the human-robot interaction of a powered knee exoskeleton. As the device was a unilateral single joint orthotic, restrictions on marker placement would have been minimal and the data presented were not representative of a full-body LEXO.

It is well established that speed can influence almost all aspects of gait (Kirtley et al*.,* 1985; Schwartz et al., 2008; Chung and Wang, 2010) and that individuals affected by neurological or motor deficits often walk more slowly than healthy, abled-bodied individuals (Lelas et al*.,* 2003; Hanlon and Anderson, 2006). Comparing gait data between clinical populations and healthy controls has become almost routine, however this could lead to unreasonable goal setting expectations for individuals with different pathologies. Hanlon and Anderson (2006) suggested that maximising an individual's function at their self-selected speed should be the primary outcome of gait rehabilitation. As a result, 'normal' speed dependent kinematic changes should be expected (i.e., reduced hip hyperextension as a result of naturally slower walking speed in healthy, able-bodied individuals). The same may be suggested of LEXO devices; it has been established that most individuals using overground LEXOs typically ambulate between 0.14 - 0.4 $m \cdot s^{-1}$ (Louie et al., 2015; Arazpour et al*.,* 2014). Therefore, kinematic profiles matching these speeds could be expected. However, to the best of the authors' knowledge, no previous research has compared the gait patterns of healthy able-bodied individuals walking at such slow walking speeds with LEXO gait.

The ReWalk$^{TM}$ (ARGO Medical Technologies Ltd, Yokneam, Israel) is a commercially available overground LEXO, with United States of America Federal Food and Drug Administration approval and European Union CE marking (He et al., 2017) which provides external support through seven articulated rigid segments around the lower limbs and pelvis. It uses motors at the hip and knee joints to drive flexion and extension movements, facilitating an externally powered gait pattern based on the user's body orientation. This arrangement controls the movement of the lower limbs whilst leaving the upper body freely moveable. Several studies have evidenced the safety of the ReWalk$^{TM}$ (Zeilig, et al*.,* 2012 & Esquenazi, et al., 2012), and have reported on the reduced physiological cost of powered LEXO walking, as opposed to non-powered reciprocating gait orthoses (Arazpour, et al., 2013) for SCI individuals. However, to date no studies have investigated the effects of LEXO use on whole-body kinematics or on ground reaction forces (GRFs) other than the vertical component. Furthermore, no studies have compared user kinematics with speed-matched able-bodied walking. Gait rehabilitation protocols and activities often initially start at slow speeds, with the intent to increase walking speed to a self-selected (more functional) level over time (Swinnen et al., 2013). These initial slow walking speeds may more closely resemble those that can be achieved using LEXO devices.

The purpose of this study was to compare the 3D gait parameters of able-bodied individuals walking overground with the ReWalk$^{TM}$, and without a LEXO at two different speeds: self-selected comfortable (CMBL) vs. slow (SLOW), speed-matched to the LEXO. This information may inform practitioners on the use of LEXOs during different stages of a person's rehabilitation, and according to their rehabilitation goals. The primary objective was to evaluate the effects of the device on the temporal-spatial and whole-body kinematic gait parameters. The secondary objective was to compare the individual GRF components with and without the device. It was hypothesised that: 1) walking with the ReWalk$^{TM}$ would alter the temporal-spatial characteristics of the gait cycle to resemble those of SLOW walking; 2) SLOW walking and LEXO gait would present with similarly reduced angles and RoM at the hip, knee and ankle (device-controlled joints) relative to CMBL walking, but that LEXO walking would elicit increased excursions of the trunk and pelvis; and 3) based on the work of Fineberg et al. (2013), peak vGRFs would be similar across all three conditions despite the use of crutches (in the LEXO condition) and different walking velocities. It was however anticipated that any differences identified would be smallest between the two speed-matched conditions.  It was also hypothesised that the anterior-posterior forces would be lower in the LEXO condition, because of the lack of propulsion required to move the limb into swing due to robotic control.

## ***2. Methods***

### *2.1. Participants*

Eight able-bodied participants (mean[SD]: age 28[6] years: height 1.72[0.04] m; mass 77[7] kg) completed this study. They were healthy adults between 23-42 years old and 165–178 cm tall, with a mass of 68-90 kg, without neurological, mobility or musculoskeletal injury. Ethical approval was provided by the University departmental review board. All participants gave written informed consent prior to testing.

### *2.2. Protocol*

Participants were fitted for the ReWalk$^{TM}$ on their initial laboratory visit and standardised settings were programmed according to manufacturer specifications (ReWalk$^{TM}$, 2014). Step initiation was triggered at 7$^{o}$ anterior tilt of the pelvic bracket sensor. Peak hip and knee flexion angles were set at 22$^{o}$ and 46$^{o}$, respectively. Peak hip extension was fixed at 8$^{o}$. Step time was set to 700 msec and the minimum delay between steps was set to 0 msec. Participants were required to use elbow crutches (during the LEXO condition only, similarly to the study conducted by Fineberg et al. (2013)) and were provided with footwear that fit the LEXO footplates.

Participants wore form fitting clothing throughout. During the CMBL and SLOW speed walking conditions, participants wore their own flat footwear and 81 retro-reflective markers (14 mm). During LEXO testing, 73 markers were used to track the body due to restrictions of the LEXO (Figure 1). Body segments were defined by an endpoint or joint-centre based on anatomical locations established using the calibrated anatomical systems technique (Cappozzo et al., 1995). Clusters of tracking markers were affixed to each body segment and tracked using the six-degrees-of-freedom principles (Buczek et al., 2010). Three-dimensional kinematics were captured with ten Oqus 4.0 cameras (Gothenburg, Sweden) at 100 Hz and synchronised with two floor integrated Kistler (9286AA) force plates (Winterthur, Switzerland) sampling at 1000 Hz via Qualisys Track Manager software version 2.15 (Gothenburg, Sweden).

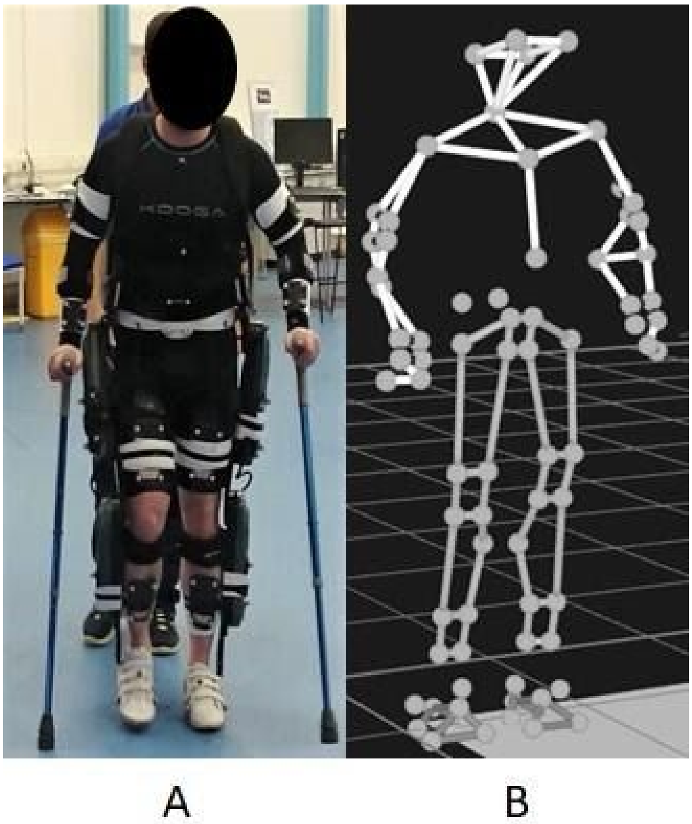

Figure 1. A) Subject wearing the ReWalk$^{TM}$ and B) Qualisys Track Manager representation of marker set.

Participants completed the CMBL speed walking trials along a 12-meter walkway at their preferred walking speed. Subsequently, the starting point of each LEXO trial was designated to facilitate GRF data collection. At least one step with each foot was required pre and post force plate contact to ensure the data were representative of steady-state gait. A LEXO gait trainer walked behind each participant to provide physical support if needed. Kinetic data were discarded if the participant made an incomplete foot contact with the force plate. Finally, the SLOW walking trials were speed-matched to the LEXO condition (0.44 m/s ± 5%), where walking speed was controlled using electronic timing gates located five meters apart (Brower Timing Systems, Utah, USA). Ten walking trials were captured and analysed for each condition; the kinematic and kinetic data were averaged across both limbs.

### *2.3. Data reduction*

3D marker coordinate and GRF data were processed in Visual 3D version 5 (C-Motion, Rockville, MD, USA). Kinematic data were interpolated using a third order polynomial. Kinematic and kinetic data were low-pass filtered using fourth order Butterworth filters (cut-off frequencies of 6 and 30 Hz, respectively). Joint kinetics were not calculated as the lower limb joints were robotically assisted by the LEXO motors. All variables were normalised to the gait cycle starting with initial contact. GRFs were normalised to body mass for CMBL and SLOW walking, and combined body + ReWalk$^{TM}$ mass for LEXO walking. All kinematic data were representative of the participant's movements inside the LEXO, allowing for a direct comparison of the user's kinematics with the CMBL and SLOW walking conditions.

### *2.4. Statistical analysis*

Temporal-spatial and vGRF load and decay rate data were analysed using a one-way repeated measures ANOVA. Post-hoc analyses with a Bonferroni adjustment were used in the event of significant findings ($P<0.05$) (SPSS statistical package V22, IBM statistics, Armonk, NY). Partial $\omega^2$ effect sizes were reported for the model and Cohen's *d* for the post-hoc tests. Established thresholds of small (0.01–0.05), medium (0.06–0.13) and large

(≥0.14) were used for interpretation of Partial $\omega^2$ (Rodriguez, 2006) and small (0.2–0.49) medium (0.5–0.79) and large (≥0.8) thresholds were used for interpretation of Cohen's *d* (Cohen, 1992). All data were assessed for normality and outliers using Shapiro-wilk test (*P>0.05*) and box plots. Outliers identified were replaced with a value either 0.01 larger than the second largest value or 0.01 smaller than the second smallest value, maintaining the spread of the data but reducing the effect of the outlier (Field, 2009). Significance (*P<0.05*) and effect size were not affected by transforming the data, therefore the original data were used in the final analysis. In the event that Mauchley's test of sphericity was violated, a Greenhouse-Geisser correction was used. Kinematic and GRF waveforms were analysed using a 1d statistical parametric mapping (SPM) one-way repeated measures ANOVA (alpha level set at 0.05) (SPM 1d ANOVArm). Post-hoc comparison t-tests with a Bonferroni adjustment (alpha level set at 0.017) were used to compare the three conditions (LEXO vs. CMBL, SLOW vs. CMBL, and SLOW vs. LEXO) over the entire gait cycle where significant differences were detected at the model level (Matlab 19a; SPM 1d). Analysis was conducted topologically and the timeframe of any significant differences between conditions were reported as a percentage of the gait cycle.

## ***3. Results***

### *3.1. Temporal-spatial characteristics*

Temporal-spatial parameters are presented in Table 1. Significant differences and large effect sizes were identified for all variables at the ANOVA level. Post-hoc analyses revealed significant differences for all variables between CMBL and SLOW gait speeds. The differences identified for double support and swing times between LEXO and SLOW gait were noteworthy as they were independent of speed, and were not evident between the CMBL and LEXO conditions.

Table 1. Mean (standard deviation) temporal-spatial data for normal, SLOW and LEXO gait (one-way repeated measures ANOVA, significance set at 95%, post-hoc test with Bonferroni correction 95% confidence intervals and Cohen's *d* effect sizes).

| | CMBL Gait | | SLOW Gait | | LEXO Gait | | |
|---|---|---|---|---|---|---|---|
| Walking speed (m/s) | 1.54 | (0.07) | 0.44 | (0.03) | 0.41 | (0.03) | F(2, 14) = 139 |
| Double support time (%) | 21 | (3.25) | 37 | (3.54) | 25 | (2.95) | F(2, 14) =57.8 |
| Cadence (steps/min) | 117 | (4) | 52 | (5) | 49 | (2) | F(2, 14) = 115 |
| Stance time (%) | 61 | (1.7) | 68 | (1.7) | 63 | (1.7) | F(2, 14) = 45. |
| Swing time (%) | 40 | (1.7) | 32 | (1.7) | 38 | (1.9) | F(2, 14) = 53. |
| Step length (% leg length) | 88 | (7.0) | 58 | (6.4) | 55 | (4.5) | F(2, 14) = 179 |
| Stride width (% leg length) | 16 | (1.8) | 20 | (2.8) | 19 | (1.6) | F(2, 14) = 14. |

| | **CMBL Gait Vs. LEXO Gait** | | | | **CMBL Gait Vs. SLOW Gait** | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Post-Hoc Analysis** | Mean Difference | Sig (*P*) | 95% Confidence Intervals | Effect Size (*d*) | Mean Difference | Sig (*P*) | 95% Confidence Intervals | Effect Size (*d*) | M Diff |
| Walking speed (m/s) | 1.11 | **<0.001** | 1.02 to 1.2 | -1.50 | 1.07 | **<0.001** | 1.0 to 1.7 | -5.04 | - |
| Double support time (%) | -4 | 0.124 | -8.7 to 1.0 | 1.09 | -16 | **<0.001** | -20.8 to -10.7 | 5.05 | |
| Cadence (steps/min) | 68 | **<0.001** | 64.2 to 71.7 | 5.93 | 66 | **<0.001** | 60.3 to 71.1 | 4.73 | |
| Stance time (%) | -2 | 0.095 | -5.2 to 0.4 | 21.8 | -8 | **<0.001** | -10.7 to -5.2 | 21.10 | |
| Swing time (%) | 2 | 0.241 | 25.6 to 33.7 | -1.2 | 8 | **<0.001** | 5.3 to 10.7 | -4.96 | |
| Step length (% leg length) | 33 | **<0.001** | -8.6 to 2.7 | 5.9 | 30 | **<0.001** | 25.6 to 33.7 | 15.36 | |
| Stride width (% leg length) | -3 | **0.020** | -5.0 to -0.5 | -1.73 | -5 | **0.005** | -7.3 to -1.7 | -2.03 | |

$\omega_p^2$ = partial omega squared

### *3.2. Joint kinematics*

Multiple biomechanical differences were evident between the three conditions, as illustrated in Figure 2. The horizontal bars at the base of each graph represent the time (as a percentage of the gait cycle) when significant differences were evident. Table 2 displays the results of the one-way repeated measures ANOVA kinematic waveforms, showing significant differences in all ten variables assessed, with post-hoc comparison results presented in Table 3. Although significant differences were identified at the model level for trunk kinematics, no differences existed between LEXO and SLOW gait. The only differences observed between CMBL and LEXO gait were in the frontal plane between 14–31% and 64–81% of the gait cycle (%GC) (loading response and push-off/early swing, respectively); there was a greater ROM in the CMBL gait condition and a difference in the waveform shape. In hip motion, SLOW gait presented with significantly less flexion compared to CMBL gait. There were, however, no differences between any of the conditions for hip extension. One of the most striking differences was the complete absence of abduction at the hip during LEXO gait, contributing to significant differences in both the CMBL and SLOW conditions at initial contact, during the loading response and swing phase. See appendix 1 for full SPM output.

Table 2. SPM one-way repeated measures ANOVA results for CMBL, LEXO and SLOW gait kinematics (critical threshold was set at 95 % and is reported as the threshold F-statistic).

| **ANOVA** | Cluster threshold F statistic | Number of clusters exceeding threshold | P Value and time of occurrence (% GC) | | P Value and time of occurrence (% GC) | | P Value and occurrence | |
|---|---|---|---|---|---|---|---|---|
| Trunk (Sagittal) | 6.596 | 2 | $P = 0.029$ | 18 – 37 | $P = 0.049$ | 79 – 82 | | |
| Trunk (Frontal) | 9.148 | 2 | $P < 0.001$ | 12 – 32 | $P < 0.001$ | 61 – 82 | $P < 0.046$ | 9 |
| Trunk (Transverse) | 10.26 | 3 | $P < 0.001$ | 0 – 7 | $P < 0.001$ | 35 – 57 | $P < 0.001$ | 8 |
| Pelvis (sagittal) | 7.535 | 3 | $P < 0.001$ | 0 – 24 | $P < 0.001$ | 50 – 76 | $P = 0.050$ | 9 |
| Pelvis (frontal) | 8.992 | 2 | $P = 0.049$ | 0 – 1 | $P < 0.001$ | 4 – 100 | | |
| Pelvis (transverse) | 9.043 | 4 | $P < 0.001$ | 0 – 11 | $P = 0.023$ | 34 – 40 | $P < 0.001$ | 4 |
| Hip (sagittal) | 7.591 | 2 | $P < 0.001$ | 0 – 25 | $P < 0.001$ | 63 – 100 | | |
| Hip (frontal) | 7.581 | 2 | $P < 0.001$ | 0 – 25 | $P < 0.001$ | 54 – 100 | | |
| Knee (sagittal) | 9.197 | 2 | $P < 0.001$ | 5 – 33 | $P < 0.001$ | 49 - 81 | | |
| Ankle(sagittal) | 9.184 | 1 | $P < 0.001$ | 55 – 87 | | | | |

% GC = percentage of gait cycle

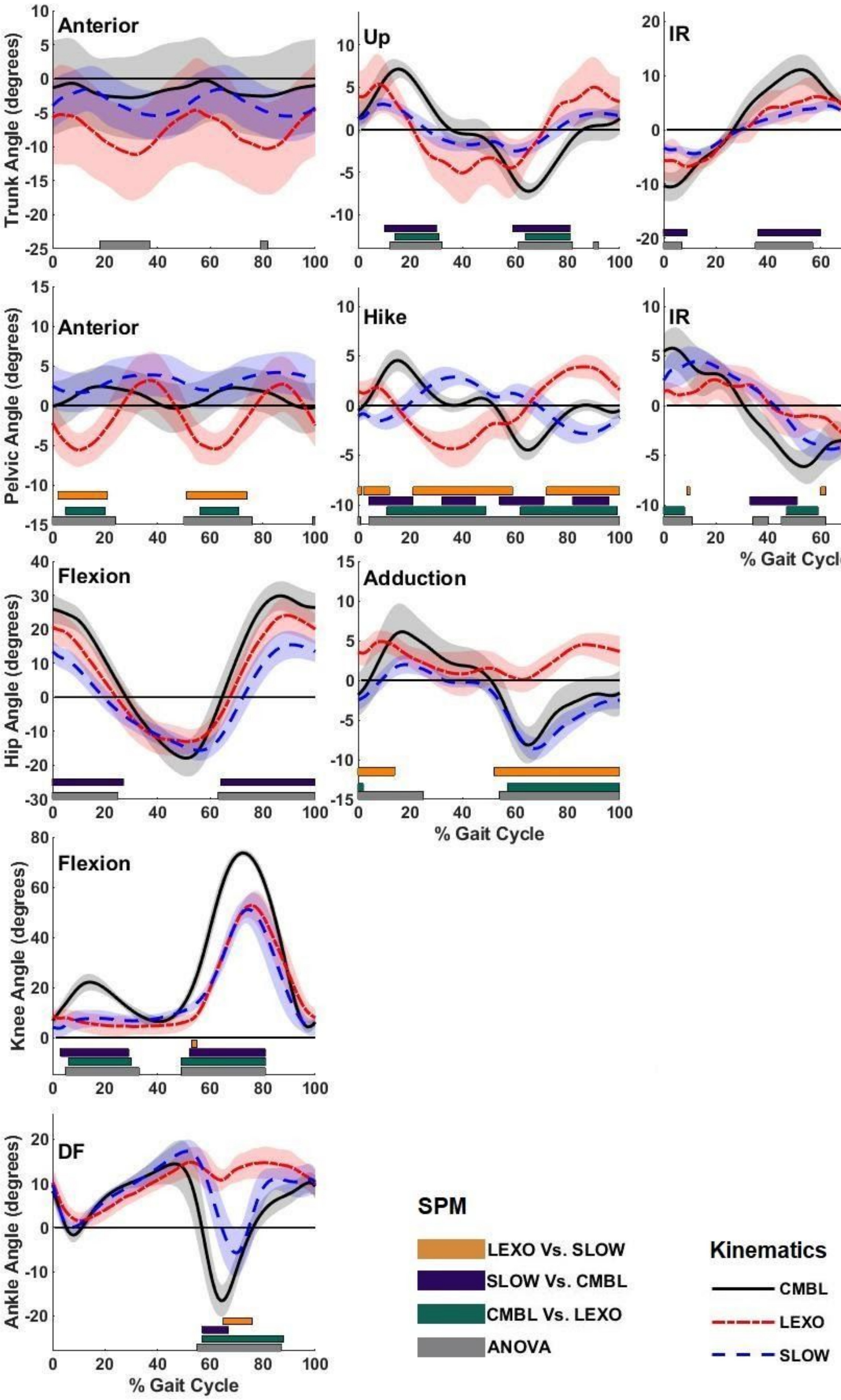

Figure 2. Trunk, pelvis, hip, knee and ankle joint angles for CMBL, SLOW and LEXO gait in the three planes of motion. The horizontal bars along the bottom of each graph represent the time period where the differences between the waveforms were significant ($P \leq 0.05$) at the

ANOVA (lowest bar) and post-hoc comparisons. 2nd bar = CMBL vs. LEXO, 3rd bar = CMBL vs. SLOW, and 4th bar = LEXO vs. SLOW, with bars described from bottom upwards.

Table 3. SPM post-hoc comparison t-tests of CMBL, LEXO and SLOW gait kinematics (critical threshold was set at 95 % and is reported as the threshold t-statistic).

| **Post-hoc analysis** | Post hoc comparison t - test | Cluster threshold t - statistic | Number of clusters exceeding threshold | P Value and time of occurrence (% GC) | | P Value and time of occurrence (% GC) | | |
|---|---|---|---|---|---|---|---|---|
| Trunk (Sagittal) | CMBL vs LEXO | 3.545 | 0 | | | | | |
| | CMBL vs SLOW | 3.413 | 0 | | | | | |
| | LEXO vs SLOW | 3.587 | 0 | | | | | |
| Trunk (Frontal) | CMBL vs LEXO | 4.213 | 2 | $P < 0.001$ | 14 – 31 | $P < 0.001$ | 64 – 81 | |
| | CMBL vs SLOW | 4.132 | 2 | $P < 0.001$ | 10 – 30 | $P < 0.001$ | 59 – 81 | |
| | LEXO vs SLOW | 4.203 | 0 | | | | | |
| Trunk (Transverse) | CMBL vs LEXO | 5.085 | 0 | | | | | |
| | CMBL vs SLOW | 4.287 | 3 | $P = 0.001$ | 0 – 9 | $P < 0.001$ | 36 – 60 | $P <$ |
| | LEXO vs SLOW | 4.437 | 0 | | | | | |
| Pelvis (sagittal) | CMBL vs LEXO | 3.808 | 2 | $P = 0.006$ | 5 – 20 | $P = 0.006$ | 56 – 71 | |
| | CMBL vs SLOW | 3.576 | 0 | | | | | |
| | LEXO vs Slow | 3.817 | 2 | $P = 0.003$ | 2 – 21 | $P = 0.001$ | 51 – 74 | |
| Pelvis (frontal) | CMBL vs LEXO | 4.152 | 2 | $P < 0.001$ | 11 – 49 | $P < 0.001$ | 62 – 99 | |
| | CMBL vs SLOW | 4.139 | 4 | $P < 0.001$ | 4 – 21 | $P = 0.001$ | 32 – 45 | $P <$ |
| | LEXO vs SLOW | 4.099 | 4 | $P = 0.016$ | 0 – 2 | $P < 0.004$ | 2 – 12 | $P <$ |
| Pelvis (transverse) | CMBL vs LEXO | 4.165 | 3 | $P = 0.004$ | 0 – 8 | $P < 0.001$ | 47 – 59 | $P =$ |
| | CMBL vs SLOW | 4.100 | 2 | $P < 0.001$ | 33 – 51 | $P < 0.001$ | 83 – 100 | |
| | LEXO vs SLOW | 4.202 | 2 | $P = 0.017$ | 9 – 10 | $P = 0.015$ | 60 – 62 | |
| Hip (sagittal) | CMBL vs LEXO | 3.810 | 0 | | | | | |
| | CMBL vs SLOW | 3.834 | 2 | $P < 0.001$ | 0 – 27 | $P < 0.001$ | 64 – 100 | |
| | LEXO vs SLOW | 3.865 | 0 | | | | | |
| Hip (frontal) | CMBL vs LEXO | 3.890 | 2 | $P = 0.017$ | 0 – 2 | $P < 0.001$ | 57 – 100 | |
| | CMBL vs SLOW | 3.863 | 0 | | | | | |
| | LEXO vs SLOW | 3.989 | 2 | $P = 0.002$ | 0 – 14 | $P < 0.001$ | 52 – 100 | |
| Knee (sagittal) | CMBL vs LEXO | 4.195 | 2 | $P < 0.001$ | 6 – 30 | $P < 0.001$ | 49 – 81 | |
| | CMBL vs SLOW | 4.268 | 2 | $P < 0.001$ | 3 – 29 | $P < 0.001$ | 52 – 81 | |
| | LEXO vs SLOW | 4.179 | 1 | $P = 0.015$ | 53 – 55 | | | |
| Ankle (sagittal) | CMBL vs LEXO | 4.154 | 1 | $P < 0.001$ | 57 – 88 | | | |
| | CMBL vs SLOW | 4.233 | 1 | $P = 0.001$ | 57 – 67 | | | |
| | LEXO vs SLOW | 4.175 | 1 | $P = 0.001$ | 65 – 76 | | | |

% GC = percentage of gait cycle

### *3.3. Ground reaction forces*

GRF SPM results are reported in Table 4, load and decay rates are reported in Table 5, and GRF profiles are presented in Figure 3. The vertical GRF profile presented in Figure 3 clearly shows that the reduced speed of SLOW and LEXO gait flattened the typical double hump curve, generated during CMBL gait, leading to significant differences between the CMBL condition and the other two conditions between 22 – 39 %GC. The only difference in the vGRF between the SLOW and LEXO conditions occurred during terminal stance/push-off (60-69 %GC) when a longer stance phase was observed in the SLOW condition. There was however no significant difference in decay rate between the LEXO and SLOW conditions (mean difference 0.16 N/kg/s, $P = 1.000$). Significantly greater braking and propulsive forces were evident during CMBL walking compared to the other two conditions.

Table 4. SPM one-way repeated measures ANOVA and post-hoc comparison t-test results for CMBL, LEXO and SLOW gait ground reaction forces (critical threshold was set at 95 % and is reported as threshold F-statistic and threshold t-statistic respectively).

| **ANOVA** | Cluster threshold F statistic | Number of clusters exceeding threshold | P Value and time of occurrence (% GC) | | P Value and time of occurrence (% GC) | | |
|---|---|---|---|---|---|---|---|
| Medial – lateral GRF | 13.763 | 4 | *P* < 0.001 | 2 – 5 | *P* < 0.001 | 11 – 12 | *P* |
| Anterior – posterior GRF | 13.763 | 3 | *P* < 0.001 | 3 – 24 | *P* < 0.001 | 36 – 56 | *P* |
| Vertical GRF | 13.763 | 4 | *P* < 0.001 | 1 – 2 | *P* < 0.001 | 4 – 13 | *P* |

| **Post-hoc analysis** | **Post hoc comparison t - test** | **Cluster threshold t - statistic** | **Number of clusters exceeding threshold** | **P Value and time of occurrence (% GC)** | | **P Value and time of occurrence (% GC)** | | |
|---|---|---|---|---|---|---|---|---|
| Medial – lateral GRF | CMBL vs LEXO | 5.080 | 2 | *P* < 0.001 | 3 – 5 | *P* < 0.001 | 55 – 57 | |
| | CMBL vs SLOW | 5.080 | 2 | *P* < 0.001 | 11 – 13 | *P* < 0.001 | 53 – 62 | |
| | LEXO vs SLOW | 5.080 | 0 | | | | | |
| Anterior – posterior GRF | CMBL vs LEXO | 5.080 | 4 | *P* < 0.001 | 6 – 23 | *P* < 0.001 | 36 – 38 | *P* |
| | CMBL vs SLOW | 5.080 | 3 | *P* < 0.001 | 4 – 22 | *P* < 0.001 | 41 – 55 | *P* |
| | LEXO vs SLOW | 5.080 | 2 | *P* < 0.001 | 62 - 66 | *P* < 0.001 | 66 - 70 | |
| Vertical GRF | CMBL vs LEXO | 5.080 | 2 | *P* < 0.001 | 23 – 37 | *P* < 0.001 | 63 - 65 | |
| | CMBL vs SLOW | 5.080 | 3 | *P* < 0.001 | 5 – 12 | *P* < 0.001 | 22 – 39 | *P* |
| | LEXO vs SLOW | 5.080 | 3 | *P* < 0.001 | 60 – 64 | *P* < 0.001 | 65 – 68 | *P* |

% GC = percentage of gait cycle

Table 5. Mean (standard deviation) vertical GRF load and decay rate data for CMBL, SLOW and LEXO gait (one-way repeated measures ANOVA, significance set at 95%, post-hoc test with Bonferroni correction 95% confidence intervals and Cohen's *d* effect sizes).

| (N/Kg) | CMBL Gait | | SLOW Gait | | LEXO Gait | | |
|---|---|---|---|---|---|---|---|
| Load rate (N/kg/s) | 8.22 | (1.92) | 1.62 | (0.47) | 1.83 | (0.71) | F(2, 14) = 69.5 |
| Decay rate (N/kg/s) | -9.34 | (1.38) | -1.57 | (0.41) | -1.73 | (0.74) | F(2, 14) = 139 |

| **Post-Hoc Analysis** | **CMBL Gait Vs. LEXO Gait** | | | | **CMBL Gait Vs. SLOW Gait** | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **(N/Kg)** | Mean Difference | Sig (*P*) | 95% Confidence Intervals | Effect Size (*d*) | Mean Difference | Sig (*P*) | 95% Confidence Intervals | Effect Size (*d*) | M Diff |
| Load rate (N/kg/s) | 6.38 | **<0.001** | 3.97 to 8.80 | 4.72 | 6.60 | **<0.001** | 4.38 to 8.81 | 5.05 | |
| Decay rate (N/kg/s) | 7.61 | **<0.001** | 5.55 to 9.67 | 7.32 | 7.77 | **<0.001** | 5.94 to 9.59 | 8.13 | |

$\omega_p^2$ = partial omega squared

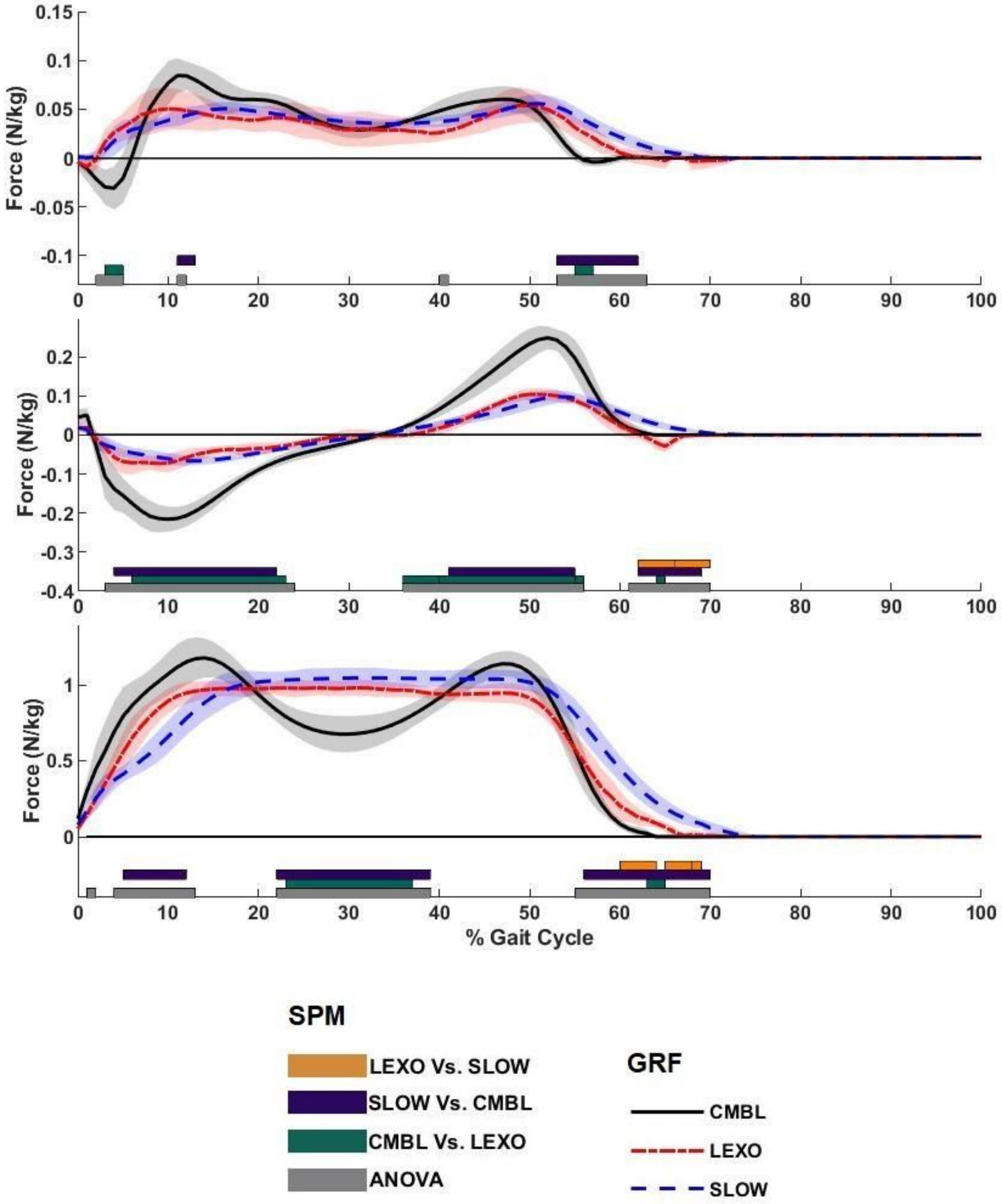

Figure 3. Medial-lateral, anterior-posterior and vertical ground reaction forces. Data were normalised to body mass or body mass and LEXO mass dependent upon condition. The gait cycle commences and terminates with ipsilateral foot contact. The horizontal bars along the bottom of each graph represent the time period where the differences between the waveforms are significant (*P* ≤ 0.05) at the ANOVA (lowest bar) and post hoc comparisons. 2nd bar = CMBL vs. LEXO, 3rd bar = CMBL vs. SLOW, and 4th bar = LEXO vs. SLOW, with bars described from bottom upwards.

## *4. Discussion*

Few studies (Ramanujam et al., 2017, Hidler et al., 2008 & Knaepen et al., 2014) have quantified the movement characteristics of the user inside a LEXO, limiting our understanding of how these devices impact the body. The aim of this study was to compare the gait parameters of able-bodied individuals walking with a LEXO, and at different speeds without a LEXO, to identify the differences in gait kinematics and kinetics independent of speed. Although other studies have provided information on the lower limb kinematic and GRF characteristics of LEXO use (Fineberg et al*.,* 2013; Arazpour et al., 2014; Ramanujam et al., 2017; Hidler et al., 2008; Knaepen et al., 2014), the current study is the first to focus on the user's whole body kinematics for an overground LEXO, and the first to compare LEXO gait to speed-matched able-bodied walking.

This and previous studies have reported slow walking speeds for able-bodied individuals using LEXOs: 0.40 m/s and 0.25–0.87 m/s respectively (Ramanujam et al., 2017; Arazpour et al., 2014; Hidler et al*.,* 2008). Speed influences a number of gait parameters during unaided walking, including swing and support times, joint kinematics and dynamic stability (Kerrigan et al*.,* 1998) as evidenced in this study. It was hypothesised that the temporal-spatial characteristics of LEXO gait would resemble those of SLOW gait, as this was speed-matched to the LEXO condition. The results in Table 2 clearly show the differences between CMBL and SLOW walking as all variables were significantly different. When comparing SLOW and LEXO gait, the most meaningful difference was the time in swing phase. Participants spent an average of 6 %GC longer in swing using the LEXO, more closely resembling the stance:swing ratio (60:40) seen at a CMBL gait speed than the hypothesised similarity to speed-matched SLOW gait. The longer swing time with the LEXO led to a concomitant reduction in stance time, which although not significantly different to SLOW gait, presented with a large effect size (*d* = -1.38). The cumulative effect of decreased stance was reflected in the significantly shorter double support for LEXO gait relative to SLOW gait (-12 %GC) (Table 2).

Previous reports indicate that slow walking speeds enhance local dynamic stability despite increased kinematic variability when walking at preferred speeds (England and Granata, 2007; Dingwall and Marin, 2006). Reduced step length and increased double support time have been reported as common adaptations to produce a more stable gait pattern (Buzzi et al*.,* 2003), both have been identified as functions of slow walking (den Otter et al*.,* 2004; Sekiya and Nagasaki, 1998) and were evident in the SLOW condition in the current study. Reduced step length in the LEXO condition was a result of the pre-programmed RoM rather than a balance strategy. Furthermore, the temporal control of the LEXO appears to have removed the capacity for individuals to utilise increased double support time as a strategy to maintain local dynamic stability. The shorter double support time could have compromised dynamic stability. Consequently, the unrestrained trunk segment likely compensated for this instability with increased medial-lateral motion. Step time is a programmable feature of the ReWalk$^{TM}$ and controls the time spent in swing. Double support was user-controlled, as the ReWalk$^{TM}$ allows a period of time to be programmed after terminal swing in which the tilt sensor is unresponsive. By setting this latency to 0 ms, any temporal variations in stepping were a direct result of the user. Step initiation was triggered through the user’s body orientation, and differences in the time taken to achieve appropriate positioning would have influenced this temporal component. Step initiation was triggered only once the tilt sensor interpreted a 7° anterior tilt orientation.

Recent work into the influence of proprioceptive feedback on neural plasticity and gait re-education after SCI has highlighted the importance of trunk control (Moraud et al., 2018). The head, arms and trunk (HAT) are typically described as a passenger unit during gait. Maintaining dynamic balance inflicts a continuous state of instability that can only be controlled by placing the swinging limb antero-laterally to the falling COM (Horak 2006; Winter et al., 1990). During stereotypical able-bodied gait, individuals are able to process environmental and afferent information, adjusting foot placement accordingly to maintain dynamic control. Use of a LEXO prevents this control strategy, even for able-bodied individuals. Although they are capable of processing the stimuli, they cannot influence the speed or position of the pre-programmed step of the LEXO. Consequently, alternative postural control strategies, using the freely moving upper body segments and walking aids (crutches), must be adopted with the LEXO, especially in light of the requirement to orientate the HAT to facilitate ongoing stepping.

Able-bodied individuals, with intact central nervous systems were used in this study to ensure any differences in gait between the conditions were relative to the condition and not the capacity of the individual to control their trunk orientation. In all three conditions the trunk maintained a posterior tilt (Figure 2). Leardini et al. (2013) suggested that a continuous backward lean of the trunk when walking reduces trunk motion during toe-off. At toe-off, the individual transfers their mass antero-laterally as body-weight moves from the trail foot onto the lead foot and into the more challenging single support phase. At the ANOVA level a significant difference was identified between the conditions in the sagittal plane (at 18–37 and 79–82 %GC). Although post-hoc comparisons revealed no differences between the conditions in the sagittal plane, frontal plane kinematics showed significant differences between both the SLOW and LEXO conditions with respect to CMBL walking (Table 3).The difference in the frontal plane trunk kinematics between the SLOW and CMBL conditions was due to the reduced RoM in the SLOW condition. However, in the LEXO condition, it was evident that the trunk had already begun to shift laterally toward the contralateral lead leg, most likely due to the use of the ipsilateral crutch to lever the body towards the contralateral side and to facilitate toe clearance, leading to an altered upper body orientation relative to CMBL walking.

It was anticipated that a side-to-side motion (generated through the use of crutches) would elicit an increased frontal plane RoM of the trunk and pelvis during LEXO gait. Although the frontal plane trunk RoM during LEXO walking did not exceed that of the CMBL condition (Figure 2), the altered timing of directional changes is clearly evident for both the trunk and pelvis. No trunk obliquity differences were evident between the LEXO and SLOW conditions; however, multiple occurrences of differing obliquity are evident at the pelvis, as all three conditions presented with radically different waveforms (Figure 2). Several authors have reported reduced pelvic obliquity during slower walking as part of an overall reduction in pelvic movement (Romkes et al., 2017; Swinnen et al., 2013; Taylor et al., 1999). It is also possible that, to help maintain postural control during the SLOW and LEXO conditions, a wider stride width was adopted (Table 1), resulting in reduced hip adduction and pelvic hike (Bruijn and van Dieen, 2018). In the LEXO condition, pelvic drop during stance would have been as a consequence of contralateral pelvic hike during toe off, as described above. The pelvic hike during swing also explains the lack of hip abduction compared to the other conditions (52-100 %GC) (Figure 2 and Table 3), as the pelvis rises ipsilaterally and the weight of the limb falls medially, the hip joint adducts.

Swinnen et al. (2015) reported reductions in trunk and pelvic excursions of able-bodied users of the Lokomat®, but increased pelvic tilt RoM. The use of an overground LEXO system in this study produced augmented pelvic tilt profiles, similar to Swinnen et al. (2015). However, in the current study, the other kinematic components of the trunk and pelvis were not reduced compared to CMBL walking. The body-weight support system of the Lokomat® impedes HAT motion and prevents limb-to-limb weight transfer, a main component of dynamic postural control (Pennycote et al., 2012). Overground LEXO gait presents potentially important benefits for training dynamic postural control, that are not achieved through treadmill-based LEXO gait when the trunk is constrained by a body-weight support system.

The sagittal plane kinematics of the lower limbs were significantly reduced during SLOW vs. CMBL walking. Table 3 shows hip flexion to be significantly lower during early stance and throughout the swing phase (0-27 and 64-100 %GC). During LEXO use, the user’s ankle was restricted by the spring-loaded mechanical joint, thereby preventing plantarflexion. The walking speed of the SLOW and LEXO conditions removed the need for knee flexion during loading, and knee flexion was not programmed into the movement pattern of the LEXO during loading. It was hypothesised that LEXO lower limb kinematics would resemble those of SLOW walking, and it appears that only the ankle joint kinematics were significantly different to those of SLOW gait.

The reduced speed of SLOW and LEXO gait caused the significantly reduced GRF components compared to CMBL gait (Figure 3). Moreover, the significantly lower vGRFs seen in the SLOW and LEXO conditions differed from the results presented by Fineberg et al. (2013) who indicated that LEXO gait (with no external assistance from a therapist) generated similar vGRF for both discrete peak values and pattern. This is the first study to investigate the horizontal GRF components in LEXO gait. The significantly slower walking speed in the LEXO and SLOW conditions reduced the peak horizontal GRFs relative to the CMBL condition. No differences were found between the SLOW and LEXO gait for the medial-lateral GRF component, but both were significantly different to that of CMBL walking during weight acceptance and push-off (Table 4). The altered medio-lateral trunk obliquity seen in LEXO gait, relative to SLOW gait, may not have changed the GRF component for two reasons. Firstly, the use of non-instrumented crutches will have generated a GRF that was not recorded; and secondly, as seen in the work of Mundermaan et al. (2008), increased medio-lateral trunk sway of $10^{o}$ (± $5^{o}$) did not present with any significant differences in lateral GRF for healthy able-bodied individuals.

The most notable vGRF differences for SLOW and LEXO gait were load and decay rates. Load rate in CMBL walking was on average 6.38 and 6.60 N/kg/s greater than in the LEXO and SLOW conditions, respectively. Similarly the CMBL decay rate was on average -7.77 and -7.61 N/kg/s greater than the LEXO and SLOW conditions (Table 5). This suggests that, although the peak forces were comparable across the three conditions, the individuals experienced them very differently during two critical sub-phases in stance.

It should be acknowledged that the current study used able-bodied participants who would normally not use a LEXO device. Although individuals with neurological movement disorders, who may use a LEXO, have varying levels of movement control, able-bodied participants were recruited as any differences identified between the conditions could then be attributed to the device and not the individual’s capacity to walk. The results of the current study were also obtained from a small sample and the data were only specifically relevant to the ReWalk$^{TM}$ (no other LEXO devices). It is also acknowledged that data for the left and right limbs were averaged across all three conditions. Although a common methodology, it is possible that any asymmetry and inter-limb variability may therefore have been masked (Sadeghi et al., 2000). Another limitation was that the GRFs from the LEXO condition were only representative of overground bipedal locomotion with walking aids. Although the elbow crutches were used predominantly for guidance, without force transducers embedded into the crutches, it was impossible to quantify how much weight was borne through the upper limbs. Nonetheless, the capacity of overground LEXO devices to provide postural control training has emerged as a finding of this research. Future work should investigate the impact of crutches on the GRFs of LEXO walking. Understanding the interaction between the individual and the LEXO device, in both able-bodied and neurologically impaired populations, should also be undertaken to ascertain how closely the SCI user follows the prescribed movement patterns.

## ***5. Conclusion***

The current study is the first of its kind to quantify the movement characteristics of the whole-body inside a LEXO during overground LEXO walking. The findings highlight the significant temporal-spatial, kinematic and GRF differences between able-bodied gait with and without a LEXO at CMBL and SLOW speeds. The SLOW condition provided the opportunity to identify biomechanical differences between able-bodied and LEXO gait that were independent of speed. The complex upper body movement control needed to operate an overground LEXO may provide an important functional balance and postural control training environment for mobility impaired individuals that warrants further investigation. The use of SPM analysis allowed the comparison of the full waveform of both kinematic and kinetic data, facilitating an understanding of the movement characteristics of LEXO users. By appreciating the differences to able-bodied slow gait, rehabilitators may be able to identify other areas of motor control that are not targeted through LEXO use, and therefore require alternative therapies.

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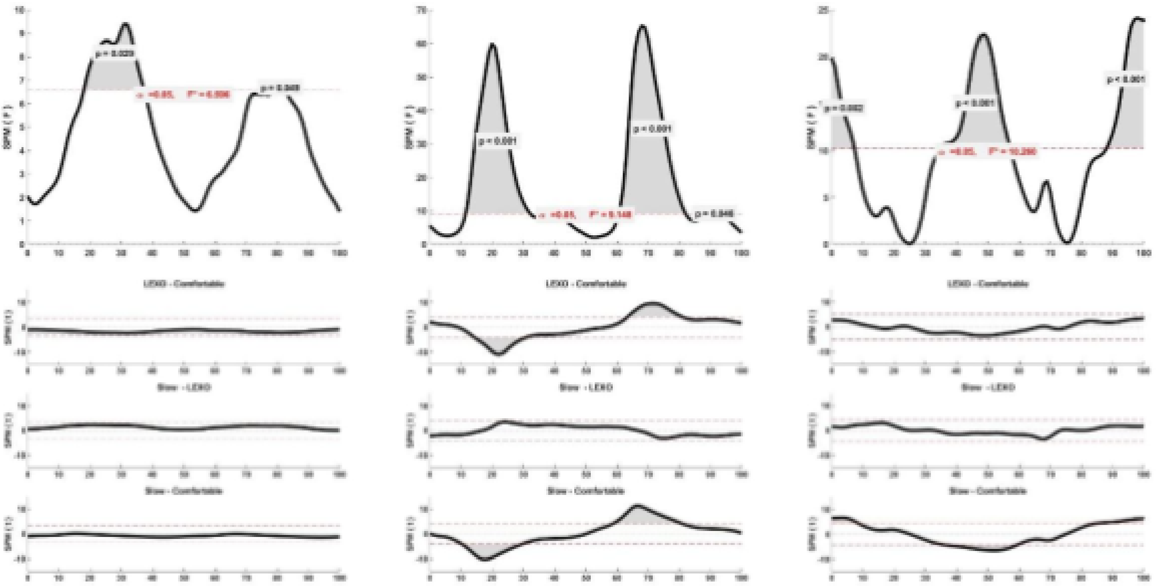
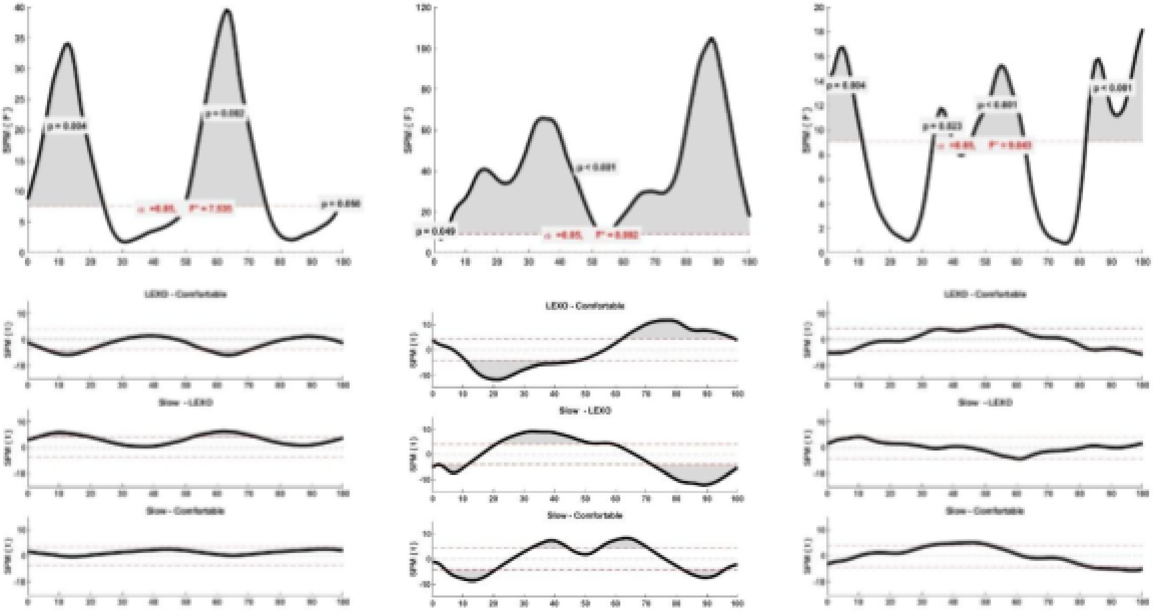
# Appendix 1 – SPM output



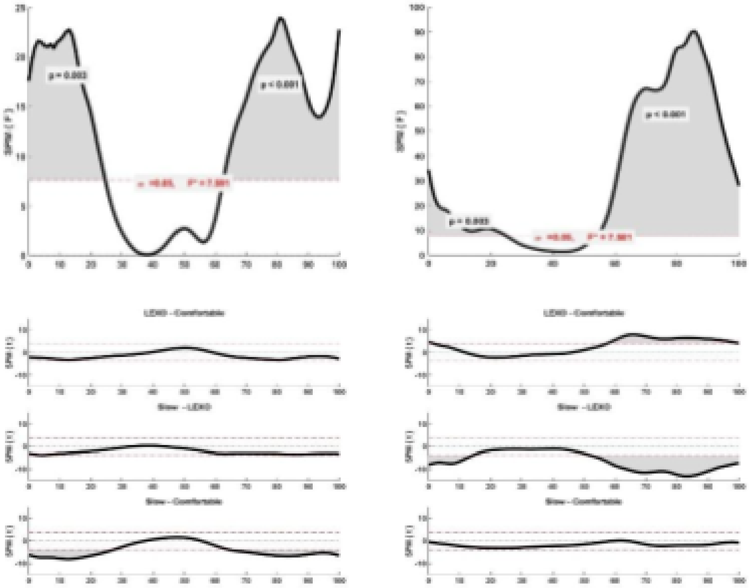
A B C

Figure 1. SPM one-way repeated measures ANOVA output for trunk kinematics in the A) sagittal, B) frontal and C) transverse planes with associated post hoc comparisons below.



A B C

Figure 2. SPM one-way repeated measures ANOVA output for pelvis kinematics in the A) sagittal, B) frontal and C) transverse planes with associated post hoc comparisons below.



A B

Figure 3. SPM one-way repeated measures ANOVA output for hip kinematics in the A) sagittal and B) frontal planes with associated post hoc comparisons below.

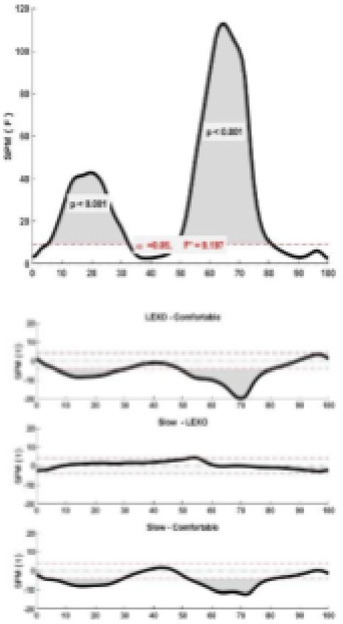


Figure 4. SPM one-way repeated measures ANOVA output for knee kinematics in the sagittal plane with associated post hoc comparisons below.

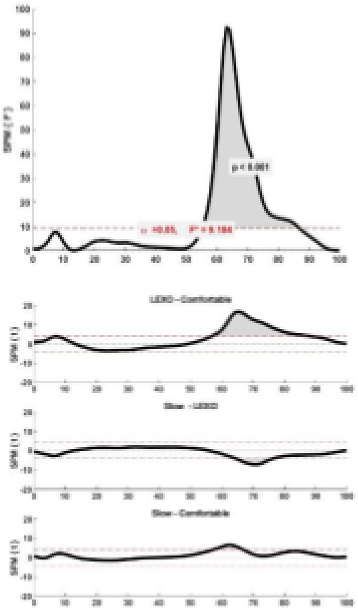


Figure 5. SPM one-way repeated measures ANOVA output for ankle kinematics in the sagittal plane with associated post hoc comparisons below.