Research article

Vertical ground reaction force-based analysis of powered exoskeleton-assisted walking in persons with motor-complete paraplegia

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Objective: To use vertical ground reaction force (vGRF) to show the magnitude and pattern of mechanical loading in persons with spinal cord injury (SCI) during powered exoskeleton-assisted walking.
Research design: A cross-sectional study was performed to analyze vGRF during powered exoskeleton-assisted walking (ReWalk™: Argo Medical Technologies, Inc, Marlborough, MA, USA) compared with vGRF of able-bodied gait.
Setting: Veterans Affairs Medical Center.
Participants: Six persons with thoracic motor-complete SCI (T1–T11 AIS A/B) and three age-, height-, weight- and gender-matched able-bodied volunteers participated.
Interventions: SCI participants were trained to ambulate over ground using a ReWalk™. vGRF was recorded using the F-Scan™ system (TekScan, Boston, MA, USA).
Outcome measures: Peak stance average (PSA) was computed from vGRF and normalized across all participants by percent body weight. Peak vGRF was determined for heel strike, mid-stance, and toe-off. Relative linear impulse and harmonic analysis provided quantitative support for analysis of powered exoskeletal gait.
Results: Participants with motor-complete SCI, ambulating independently with a ReWalk™, demonstrated mechanical loading magnitudes and patterns similar to able-bodied gait. Harmonic analysis of PSA profile by Fourier transform contrasted frequency of stance phase gait components between able-bodied and powered exoskeleton-assisted walking.
Conclusion: Powered exoskeleton-assisted walking in persons with motor-complete SCI generated vGRF similar in magnitude and pattern to that of able-bodied walking. This suggests the potential for powered exoskeleton-assisted walking to provide a mechanism for mechanical loading to the lower extremities. vGRF profile can be used to examine both magnitude of loading and gait mechanics of powered exoskeleton-assisted walking among participants of different weight, gait speed, and level of assist.

Keywords: Spinal cord injury, Paraplegia, Rehabilitation, ReWalk™, Assistive technology, Robotic-assisted exoskeletal device, Vertical ground reaction force, Mechanical loading, F-scan™ tekscan, Fourier series

Introduction

Many individuals with spinal cord injury (SCI) are able to ambulate overground with assistive devices. Unpowered exoskeletons, including ankle-knee-foot orthoses (AKFO), reciprocating-gait orthoses (RGOs) and advanced reciprocating-gait orthoses (ARGOs), have been used with some success in those with incomplete spinal lesions who have good upper body strength and control.[1] Robotic exoskeletons employ powered mechanical joints, and have emerged as the next step in the technological evolution of exoskeletons. While

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unpowered exoskeletons (AKFO, RGO, and ARGO) have been shown to facilitate over ground ambulation in motor-incomplete SCI, efficacy in persons with motor-complete SCI is limited by the high energy cost that is associated with their use.[2,3] A unique aspect of a powered exoskeleton-assisted walking device is its ability to provide maximum support for overground walking in a person with motor-complete SCI, with minimal, but sustainable, effort from the user. Recent studies have shown powered exoskeletons to be effective in facilitating overground ambulation in the population with motor-complete SCI;[4–6] however, exoskeletal gait pattern has yet to be examined. Vertical ground reaction force (vGRF) represents the magnitude and pattern of mechanical loading in the vertical direction at the foot,[7] and it is commonly used in the diagnosis of atypical gait. Analysis of vGRF can be applied to exoskeletal ambulation to discern the magnitude and mechanism by which loading occurs. The F-Scan™ (TekScan, Boston, MA, USA) in-shoe pressure mapping system has been effectively used to measure vGRF during able-bodied walking.[8] vGRF profile reflects critical gait components, and has been used to perform gait analysis on a variety of atypical neuropathic gaits.[9,10] It was hypothesized that analyses of vGRF during powered exoskeleton-assisted walking would show lower force loading magnitudes, yet comparable to those of able-bodied gait, and these analyses would reflect characteristic components of an exoskeletal gait. The vGRF profiles in participants of different weights and gait speeds during powered exoskeleton-assisted walking were analyzed and compared to able-bodied controls walking without a powered exoskeleton.

Methods

Setting

Veterans Affairs Medical Center (VAMC), Rehabilitation Research and Development Service National Center of Excellence for the Medical Consequences of Spinal Cord Injury.

Participants

Participants with chronic, motor-complete thoracic SCI ($n = 6$; one woman, and five men; 24–61 years old), and able-bodied controls ($n = 3$; one woman, and two men; 32–55 years old) were recruited for study. Informed consent was obtained prior to participation in the study protocol. The study was approved by the VAMC Institutional Review Board. Participants with SCI were trained to walk using a powered exoskeleton, during which in-shoe pressure mapping was performed.

Training for powered exoskeleton-assisted walking

Device operation

A powered exoskeleton (ReWalk™; Argo Medical Technologies, Inc, Marlborough, MA, USA) is currently under study at the VAMC and elsewhere to facilitate overground ambulation in individuals with motor-complete paraplegia. The powered exoskeleton was adjusted to fit each participant with specific focus provided to alignment of anatomical and exoskeleton joint centers. Participants were secured in the device with a series of straps; padding was added to regional sites as needed to prevent possible skin abrasion. The ReWalk™ foot plates were inserted between the insole and shoe, enabling participants to use their own shoes. In the event that the participant's shoes were not conducive to powered exoskeleton-assisted walking, active walker, or athletic walker model shoes (Aetrex Worldwide, Inc., Teaneck, NJ, USA) were used. Participants initiated sit-to-stand, stand-to-sit, and walk modes using a wireless controller. After walk mode was selected, the participant initiated and propagated ambulation by forward lean and coordinated weight shifting. The powered exoskeleton supported the participant from the lower extremities through a pelvic band, straps at the hips, upper and lower leg frames, and foot plates worn inside the participant's shoe (Fig. 1). Although the intended use of the crutches

Figure 1 Using F-Scan™ Sensors with the ReWalk™. (A) Participant using the ReWalk™ exoskeletal device; (B) participant wearing F-Scan™ incorporated into the ReWalk™ setup; and (C) F-Scan™ in-shoe pressure sensors placed above the insole below the surface of the foot. The footplate of the ReWalk™ powered exoskeleton sits below the insole of the shoe; the weight of the ReWalk™ is not transferred onto the force sensor. *Note*: The heel strike as the participant takes a step in the ReWalk™.

is to maintain balance and guide weight shift, it was expected that a variable and undetermined degree of off-loading may occur. The only additional weight supported by the participant was from the wireless controller (worn on wrist), and the computer, primary, and backup battery (carried in backpack), which together weighed 3.5 kg.

Exoskeletal walking parameters

The powered-exoskeletal gait was designed to closely replicate normal able-bodied gait. Joint angles, walking speed, delay between steps, tilt angle, and safety parameters were uniquely determined for each participant based on individual anthropometric relationships of stature. These parameters were adjusted during training to coincide with the participant's progress. Once the participant selects walk mode on the wireless controller, ambulation is initiated and propagated by coordinated weight shift. Each step is triggered individually by leaning forward through a predetermined degree of tilt, measured by a 3D accelerometer, or tilt sensor, located at hip-height on the powered exoskeleton. The degree of tilt required to initiate a step is commensurate with amount of forward lean that the participant must perform to transfer from stance leg to swing leg. Unique walking parameters for each participant resulted in ambulation at different overground velocities; stance phase time was normalized to percent of gait cycle in peak stance average (PSA) analysis to account for this variation.

Training Program

Training sessions consisted of 1–2 hours of combined standing and walking per session, three times per week for 5–6 months. Participants were taught standing and balancing in the exoskeleton, before progressing to walking. A trainer provided varying levels of assistance and was always present during the training sessions. As participant's skill with the powered exoskeleton improved, the need for trainer input was proportionately reduced. The level of trainer assistance was quantified by the following four categories of trainer-assisted efforts: (1) maximal assistance (max-assist) – the trainer had both hands on the pelvic band of the device and provided significant and frequent weight shift and balance support to the participant during the majority of the mobility activity; (2) moderate assistance (mod-assist) – the trainer had both hands on the pelvic band or other part of the device and provided occasional weight shift and/or balance support to the participant during the mobility activity; (3) minimal assistance (min-assist) – the trainer had one hand on the device and provided infrequent balance support; and (4) close contact guard/no assistance (CCG/no-assist) – the trainer did not have either hand on the device, but was near enough to be able to provide assistance if necessary.

In-shoe pressure mapping

Setup

The F-Scan™ in-shoe pressure mapping system was used simultaneously with the powered exoskeleton to record force imparted onto the participant's feet during powered exoskeleton-assisted walking (Fig. 1B). Each pressure sensor (model 3000E) has a thickness of 0.15 mm and is composed of 960 individual sensing elements (sensels) at a density of 3.9 sensels/cm^2 over an area of 106.7 mm × 304.8 mm. Each in-shoe pressure sensor was trimmed to fit the participant's foot size; the recorded pressure profile was scaled to a 21 × 60 grid by the F-Scan™ software. The sensor was connected to a VersaTek Cuff unit, which was attached to the lower leg of the participant by a velcro band. The two VersaTek Cuff units were connected to the wireless unit that was attached to the patient with a waist strap. The wireless unit transmits sensor data at a range of 100 m to the computer containing the F-Scan™ software, where it was recorded and processed. A static calibration of each pair of sensors was performed using the F-Scan™ system's 'point calibration' feature by an able-bodied control matched to a SCI participant. The F-Scan™ system records force at each sensel, establishing a pressure profile of the area loaded in pounds per square inch or kilopascals. In-shoe pressure mapping system was used instead of conventional force platforms to exclude the vGRF generated by the weight of the exoskeleton. The net vertical normal force acting on the participant's foot was measured for participants with SCI walking with the exoskeleton and the able-bodied walking without, and for the purposes of this article is referred to as vGRF. vGRF was computed individually for left and right foot by the F-Scan™ system as the summation of force loaded across each sensor and was reported in Newtons. Data were collected at a sample rate of 50 Hz. The in-shoe pressure sensors were placed between the subject's foot and insole, with the footplate of the powered exoskeleton between the insole and the shoe (Fig. 1C). Sensor placement ensured that the weight of the powered exoskeleton would not be included in the force loading measurement, as well as including any offloading generated at the pelvic band, straps, or crutches.

Data collection

vGRF for left and right foot were measured with the F-Scan™ in participants with SCI walking over ground using the powered exoskeleton and in able-bodied participants walking normally without the powered exoskeleton. Measurements were obtained after the SCI participants were able to demonstrate 10 m of consecutive steps with minimal-assist or no-assist. Three out of the six participants with SCI performed powered exoskeleton-assisted walking with no-assist, while the other three participants required minimal-assist from trainers. The SCI group was stratified into two subgroups based on level of assist (LOA) needed: SCI no-assist and SCI min-assist.

vGRF data analysis

Peak stance average (PSA)

Left and right foot vGRF data, excluding the first and last steps, were analyzed using the PSA function of the F-Scan™ software. PSA, calculated as Newtons per percent gait cycle, was determined by a standard function of the F-Scan™ analysis software that segments each vGRF plot into an average of each consecutive step. PSA normalized the duration of stance phase time per individual step to 100% of gait cycle, thus allowing for an objective comparison of stance phase vGRF profiles among persons ambulating at different speeds. The PSA did not include first or last steps because stopping and starting force profiles are appreciated to be different from subsequent or preceding steps, respectively. PSA was normalized to percent body weight (%BW) for each individual to enable comparisons among participants of different weights. For the participants using the powered exoskeleton, the weight of the backpack and wireless controller (3.5 kg) was added to the weight of the participant for the calculation of %BW. Participants with SCI using the powered exoskeleton required different levels of trainer support, or LOA. PSA force profiles of powered exoskeleton-assisted walking were grouped by LOA (min-assist or no-assist).

PSA area under curve (relative linear impulse)

Linear impulse reflects the force imparted as a result of change in momentum. Similar to normal gait, the foot is not completely flat to the ground during heel strike and toe-off phases of the ReWalk™ exoskeletal gait. For this reason, a comparison of the PSA curves exclusively by summation of peaks or average across time points neglects to capture the global effect of impact forces generated at heel strike and toe-off. Work, or energy-based analyses of force, requires integration with respect to displacement; however, linear impulse can be calculated by integration of force with respect to time.[11] PSA normalizes the time component of vGRF-time curve to percent gait cycle; numerical integration of force with respect to percent gait cycle results in a relative linear impulse (kN percent gait cycle). Relative linear impulse was computed by trapezoidal integration of PSA using Matlab. Normalization of stance phase time to percent gait in PSA cycle resulted in 101 data points (0–100%) for each curve. A linear interpolation was performed to generate 128 data points to avoid 'zero padding' effect when performing a fast Fourier transform function using Matlab.[12] Mean PSA force was removed prior to computation to remove the effect of the zero harmonic. Harmonic analysis of powered exoskeleton-assisted walking PSA profile provides a refined look at the distribution of the stance phase gait components.

Maximum/minimum vGRF peaks

PSA profiles were indexed for key stance phase gait components: (1) peak heel strike vertical ground reaction force ($vGRF_{HS}$), (2) minimum mid-stance vertical ground reaction force ($vGRF_{MS}$), and (3) peak toe-off vertical ground reaction force ($vGRF_{TO}$).[10] $vGRF_{HS}$ corresponds to the highest vertical force measurement during the heel strike. When uninhibited by body weight support (BWS), $vGRF_{HS}$ is expected to exceed the participant's total BW due to the impulse generated by heel strike. $vGRF_{MS}$ represents the peak force experienced during mid-stance, after heel strike but before toe-off. $vGRF_{TO}$ represents the peak toe-off force responsible for generating final forward propulsion.

Harmonic analysis

Harmonic analysis by spectral representation has been demonstrated to be a useful tool for highlighting the defining characteristics of an atypical curve, and serves to provide a basis of comparison to other pathological gaits.[7] A Fourier transform tests the assumption that any curve can be represented by a potentially infinite number of sinusoids by quantifying the difference between the curve and the hypothesized sinusoidal representation. In theory, an infinite number of sine waves with harmonically relevant frequencies can be used for analysis. However, when applied to a discrete curve, the applicable number of harmonics is determined by the number of discrete data points. The first harmonic refers to the fundamental sine wave, with subsequent harmonics occurring at twice the frequency of the previous wave.

Statistical analyses

Demographic characteristics were presented individually for each participant in the study and as mean plus or minus (±) standard deviations (SD) for the three study groups. Within each participant, paired *t*-tests were used to determine differences between left and right foot PSA of vGRF. Because no statistically significant differences were noted in left and right PSA values, they were averaged to be reported as a single PSA value for each participant. Gait cycle parameters ($vGRF_{HS}$, $vGRF_{MS}$, and $vGRF_{TO}$) were reported as individual values and mean ± SD with the 95% confidence interval for the three groups (able-bodied control, SCI no-assist, and SCI min-assist). A single-factor (group) analysis of variance was used to determine the main effect differences among the three groups. Scheffe' *post hoc* tests were applied to test for single degree of freedom differences among the groups.

Results

Participant characteristics

The individual demographic information for the three groups and SCI-specific characteristics are provided (Table 1). All participants with SCI had motor-complete paraplegia with durations of injury ranging from 1.5 to 14 years. As previously stated, at the time of data acquisition, three participants with SCI were able to perform powered exoskeleton-assisted walking without assistance (SCI no-assist) and three, with minimal assistance (SCI min-assist). The able-bodied participants were studied walking with their normal gait patterns, independent of the powered exoskeleton. During vGRF testing, the SCI min-assist group had statistically slower mean walking velocity than the SCI no-assist group (0.16 ± 0.06 vs. 0.31 ± 0.02 m/second, $P = 0.0148$). As expected, both SCI groups were slower than the able-bodied controls (1.136 ± 0.32 m/second).

PSA interpretation and analysis

Stance phase time was normalized in the analysis to % gait cycle by PSA to allow for comparison of vGRF profile at varying walking speeds. $vGRF_{HS}$, $vGRF_{MS}$, and $vGRF_{TO}$ are reported as individual and mean ± SD for the three groups (Table 2). Participants in the SCI minimal-assist group demonstrated the lowest vGRF compared with the no-assist and the able-bodied controls. The SCI min-assist group was statistically lower than both the SCI no-assist and able-bodied controls for gait cycle area under the curve (AUC), expressed as relative linear impulse of PSA (4.26 ± 1.57 vs. 7.37 ± 8.01, $P < 0.05$ and 7.72 ± 1.02, $P < 0.05$ %BW/kN·%gait cycle, respectively). No significant difference was found for AUC between the able-bodied control group and the SCI no-assist group. Participants with SCI performing powered exoskeleton-assisted

Table 1 Characteristics of the study participants

SID	Group	Gender	Age (years)	Height (cm)	Mass (kg)	LOI	AIS	DOI (years)	Level of assist
1	SCI	Male	34	175	66.6	T4	B	9.0	Minimal assist
2	SCI	Male	48	168	67.5	T1	A	4.0	Minimal assist
3	SCI	Male	43	183	78.8	T4	A	4.0	No assist
4	SCI	Female	58	160	64.8	T8	A	1.5	No assist
5	SCI	Male	62	175	72.0	T11	A	14.0	No assist
6	SCI	Male	24	185	74.3	T5	A	5.0	Minimal assist
7	AB control	Male	41	185	90.7	AB			
8	AB control	Male	32	183	88.5	AB			
9	AB control	Female	55	162	49.9	AB			

SID, study identification number; LOI, level of injury; AIS, American Spinal Injury Association Impairment Scale; DOI, duration of injury; T, thoracic vertebral level.

Table 2 The results of GRF normalized to percent body weight for the participants

SID	Group	Level of assist	Session no.	Walking velocity (m/second)	Vertical ground reaction forces: Heel strike (%BW)	Mid stance (%BW)	Toe off (%BW)
1	SCI	Minimal assist	20	0.22	29	46	60
2	SCI	Minimal assist	21	0.16	54	60	85
3	SCI	No assist	41	0.29	58	98	108
4	SCI	No assist	29	0.33	74	98	115
5	SCI	No assist	45	0.31	67	77	99
6	SCI	Minimal assist	11	0.10	26	36	43
7	AB control	N/A	N/A	1.67	103	65	119
8	AB control	N/A	N/A	1.39	84	64	85
9	AB control	N/A	N/A	1.03	87	81	112

SID, study identification number; AB, able-bodied control; N/A, not applicable; %BW, percent of total body weight.

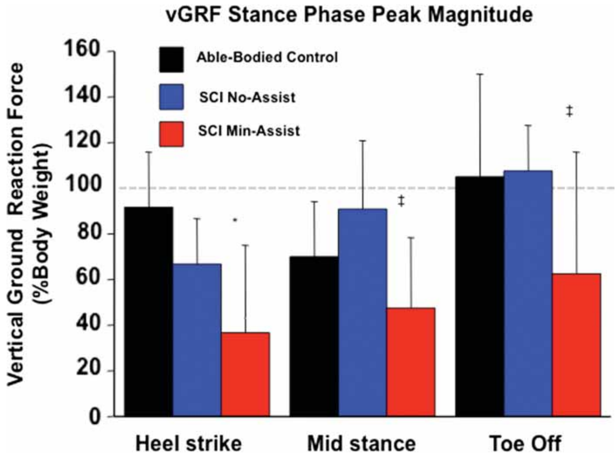

Figure 2 vGRF of stance phase component by group. Variability bars represent the 95% confidence intervals. Body weight of the SCI groups is adjusted by subtracting the backpack and remote watch weight. *SCI min-assist vs. AB control: $P = 0.0034$. ‡SCI min-assist vs. SCI no-assist: $P =$ 0.0095 and 0.0457, respectively.

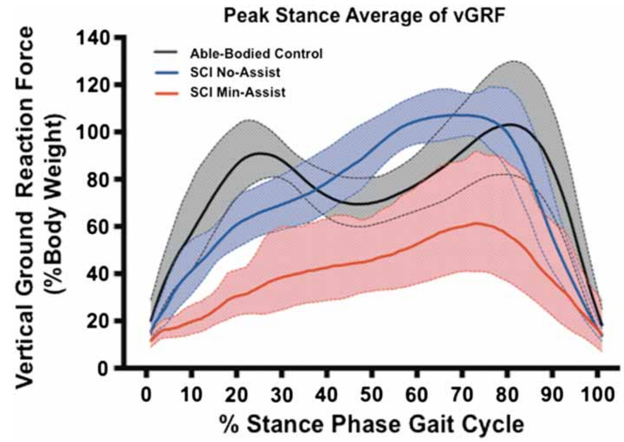

Figure 3 PSA of vGRF with error bars at 95% confidence intervals. Able-bodied controls are shown in black, participants with SCI walking in the ReWalk™ with no-assist are shown in blue, and those with min-assist are shown in red. PSA, peak stance average; GRF, ground reaction force.

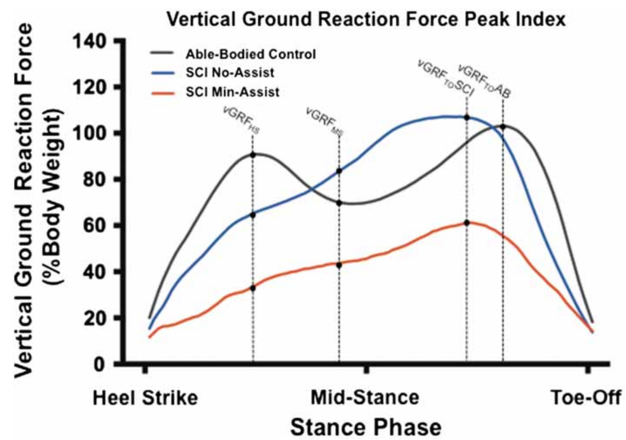

Figure 4 PSA indexed for vGRF minimum/maximum peaks. Peak stance average is shown for all groups by stance phase with error bars removed for clarity. Peak vertical ground reaction force are indexed: heel strike vertical ground reaction force, mid-stance vertical ground reaction force, and toe-off vertical ground reaction force ($vGRF_{TO}AB$, and $vGRF_{TO}SCI$). $vGRF_{TO}$ is indexed sepearately for able-bodied control group and SCI groups, as peak toe-off force occurs later in the exoskeletal gait cycle.

ambulation with no-assist generated average $vGRF_{HS}$ of $66 \pm 8\%$, $vGRF_{MS}$ of $91 \pm 12\%$, and $vGRF_{TO}$ of $107 \pm 7\%$, and those with minimal-assist generated average $vGRF_{HS}$ of $36 \pm 15\%$, $vGRF_{MS}$ of $47 \pm 12\%$, and $vGRF_{TO}$ of $62 \pm 21\%$. The able-bodied controls generated average $vGRF_{HS}$ of $91 \pm 9\%$, $vGRF_{MS}$ of $70 \pm 9\%$, and $vGRF_{TO}$ of $105 \pm 18\%$ (Table 2).

Comparisons performed of vGRF peaks between the no-assist and min-assist SCI groups demonstrated significant differences (Fig. 2). Individuals with no-assist generated significantly greater vGRF than that of the min-assist group for all three parameters, indicating the potential sensitivity of this approach to measure change (i.e. progression from min-assist to no-assist) in the level of skill over time with further training and experience in performing powered exoskeleton-assisted walking. PSA of participants grouped by LOA and able-bodied control group demonstrated that participants with SCI loaded at higher magnitudes when ambulating with no-assist than those with minimal-assist, and at comparable magnitudes to able-bodied controls (error bars of the 95% confidence intervals) (Fig. 3).

vGRF peaks are shown for the able-bodied group and applied to the SCI groups for comparison (Fig. 4). In normal walking, vGRF increased during heel strike, then decreased during mid-stance loading, and finally increased during toe-off as propulsive force was generated (Fig. 4; black tracing). In both SCI groups, there was no load dampening in mid-stance, evidenced by a continued increase in vGRF from $vGRF_{HS}$ to $vGRF_{MS}$. $vGRF_{HS}$ occurred at the same point (27% gait cycle) for SCI and able-bodied groups. $vGRF_{TO}$ occurred earlier (70% gait cycle) in both SCI groups than the able-bodied group (83% gait cycle), indicating a prolonged toe-off phase in the exoskeletal gait when compared with the able-bodied group. As such, peak toe-off force index is denoted as $vGRF_{TO}SCI$ for SCI groups walking with an exoskeleton, and $vGRF_{TO}AB$ for able-bodied control group walking without (Fig. 4).

Harmonic analysis

Harmonic analysis of vGRF by Fourier transform was compared between the first and seventh harmonic for all groups (Fig. 5). Previous use of harmonic analysis

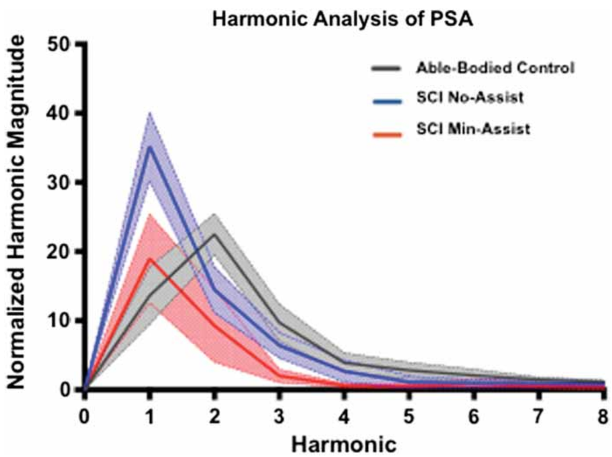

Figure 5 Harmonic analysis of PSA. Fourier transform is shown for all groups for first eight harmonics. Able-bodied control group has greater representation in the second harmonic (black) whereas SCI groups have greater representation in the first harmonic. Harmonic analysis appears to permit sufficient sensitivity to differentiate level of assistance between SCI groups of min-assist and no-assist.

by other investigators has shown that relative harmonic magnitude at harmonics greater than seven had few defining characteristics.[7] The able-bodied control group had greater representation in the second harmonic, whereas the SCI groups had the largest representation in the first harmonic. Sensitivity to magnitude of force loading was also reflected in the difference in first harmonic magnitudes of SCI groups (Fig. 5).

Discussion

Using an in-shoe pressure mapping system to capture vGRF, persons with motor-complete SCI were shown to experience mechanical loading during powered exoskeleton-assisted over ground walking. SCI participants in the no-assist group generated vGRF similar to that of normal able-bodied ambulation. Those in the SCI min-assist group were able to demonstrate vGRF at about half of that of the able-bodied control group. Defining characteristics of exoskeletal gait, as well as sensitivity to skill level of SCI participants performing powered exoskeleton-assisted walking, were reflected in PSA profile and harmonic analysis. In-shoe pressure mapping and PSA analysis provided evidence for using powered exoskeletons as a method to achieve force loading-based outcomes.

PSA analysis of vGRF demonstrated sensitivity to LOA once normalized for the weight and gait speed of the participant. Smaller vGRF for the min-assist SCI group was thought to be attributed to use of crutches by the participant for support causing dampening of heel srike and toe-off forces. Differences between exoskeletal and normal gait pattern are evident in examination of heel strike, mid-stance, and toe-off phase duration and force magnitude. A smaller $vGRF_{HS}$ in the participants of both SCI groups was assumed to be from off weighting with crutches during heel strike. In both the SCI groups, $vGRF_{MS}$ increased relative to $vGRF_{HS}$, whereas it decreased in the able-bodied group. $vGRF_{MS}$ decreased as expected in the able-bodied group due to dampening of the force loaded by the slight stance leg knee flexion when approaching mid-stance; by design, this movement does not occur in the exoskeletal gait, and thus there was no reduction in $vGRF_{MS}$. $vGRF_{TO}$ occurred earlier in the exoskeletal gait cycle than normal walking, due to the difference in toe-off mechanisms. Forward propulsion in powered exoskeleton-assisted gait was not generated by active toe-off as it occurs in normal gait; instead, the stance leg begins and sustains hip extension at an earlier time in the gait cycle. Stance leg hip extension successfully provided a forward propulsive force as long as the participant's center of mass remained weighted on and forward of the stance leg.

Interpolation of the PSA data set to contain 128 points that eliminated the 'zero padding' effect ensured the fundamental harmonic occurred at a frequency of one oscillation per length of data set. A larger representation of PSA data in lower harmonic frequencies suggests that contributing data points reflect a lower frequency than data points at subsequent harmonics. Harmonic analysis of PSA across all groups showed exoskeletal gait had a greater presence in the first harmonic, whereas able-bodied gait had the greatest magnitude in the second harmonic. The first harmonic representation in the SCI groups reflected the absence of a decrease in $vGRF_{MS}$, as well as an extended heel strike and toe-off phases. The able-bodied group presented primarily in the second harmonic, indicating the presence of a decreased $vGRF_{MS}$ relative to heel strike, and that heel strike and toe-off comprised a smaller portion of the gait cycle.

In addition to functional walking outcome measures, assisted ambulatory exercise interventions, such as long-leg braces, robotic- and manual-assisted body weight supported treadmill training (BWSTT), are routinely examined for magnitude of mechanical loading forces on the skeleton, with one of the considerations being preservation of bone health. In a study examining the effect of shock-absorbing materials on long-leg braces, it was demonstrated that a participant with a L4 motor-complete SCI weighing 50 kg loaded with a peak force of 160N, or 31% BW when ambulating overground.[13] Recent studies showed motor-complete SCI performed BWSTT starting with 60–97% BWS (3–40% BW loaded) and ending with 20–45% BWS (55–80% BW loaded).[14,15] Although a head-to-head comparison has not been performed, these levels of mechanical loading are comparable to the 48% BW loaded with min-assist and 88% BW loaded with no-assist for participants with motor-complete SCI performing powered exoskeleton-assisted walking.

There are several limitations of our preliminary study. The sample size was relatively small ($n = 6$) and was comprised predominantly of men. The vGRF profiles of persons with varying levels and completeness of injury were not determined. To compare vGRF profiles at different levels of assistance, it was inevitable that measurements were obtained at varying points in the training cycle. All participants (able-bodied and SCI) ambulated at different speeds. A PSA was used to normalize different walking velocities; however, this approach precluded time-based interpretations of vGRF. Data from one session were used for purposes of comparison among the study groups; thus, no attempt was made to assess the potential changes in the vGRF profiles of powered exoskeleton-assisted walking when participants initially required some level of assistance to that when they had acquired greater skill and independence and were able to walk in the exoskeleton without assistance.

Conclusion

PSA profile accurately represented powered exoskeleton-assisted and able-bodied gait. This approach was used in conjunction with harmonic analysis to support and quantify the comparison of stance phase gait components for powered exoskeleton-assisted and able-bodied walking. PSA effectively represented stance phase vGRF from continuous steps as a percentage of a single stance phase gait cycle, which facilitated comparison among participants ambulating at different speeds. Normalizing PSA of vGRF by %BW extended this comparison to include vGRF magnitude for participants of different weights ambulating at different speeds, and this approach showed sensitivity to be able to discern the level of skill of participants using the powered exoskeleton.

A comparison PSA area under curve (relative linear impulse) revealed that powered exoskeleton-assisted walking produced vGRF loading comparable to normal walking. Participants with thoracic motor-complete SCI experienced loading during powered exoskeleton-assisted ambulation at an average across vGRF max/min peaks of 48% BW with min-assist, and 88% BW with no-assist. Under the assumption that the %BW loaded during BWSTT is, at maximum, equal to 100% – %BWS, normalizing vGRF to %BW when evaluating powered exoskeleton-assisted walking may be a potential method for comparing mechanical loading between powered exoskeletons and BWSTT. PSA and subsequent analyses can be used to evaluate vGRF in future studies of powered exoskeletons. In future studies, vGRF-based analyses have the potential to provide force loading-based outcome measures that may correlate to changes in bone parameters as a result of dynamic force loading during powered exoskeleton-assisted walking.

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