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Device use, locomotor training, and the presence of arm swing during treadmill walking post-spinal cord injury

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Abstract

Objectives—Determine the presence of walking-related arm swing following spinal cord injury (SCI), associated factors, and whether arm swing may change following locomotor training (LT).

Design—Observational, cross-sectional study from a convenience sample with pre-test/post-test from a sample subset.

Setting—Malcom Randall VAMC and University of Florida, Gainesville, FL.

Methods—Arm movement was assessed during treadmill stepping, pre-LT, in 30 individuals with motor incomplete SCI (iSCI, American Spinal Injury Association Impairment Scale grade

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C/D, as defined by the International Standards for Neurological Classifications of SCI, with neurological level of impairment at or below C4). Partial body weight support and manual-trainer assistance was provided, as needed, to achieve stepping and allow arm swing. Arm swing presence was compared based on cervical versus thoracic neurological levels of impairment and device type. Leg and arm strength and walking independence were compared between individuals with and without arm swing. Arm swing was re-evaluated post-LT in the 21/30 individuals that underwent LT.

Results—Of 30 individuals with iSCI, 12 demonstrated arm swing during treadmill stepping, pre-LT. Arm movement was associated with device type, lower extremity motor scores, and walking independence. Among the 21 individuals that received LT, only 5 demonstrated arm swing pre-LT. Of the 16 individuals lacking arm swing pre-LT, 8 integrated arm swing post-LT.

Conclusion—Devices routinely used for walking post-iSCI appeared associated with arm swing. Post-LT, arm swing presence increased. Therefore, arm swing may be experience-dependent. Daily neuromuscular experiences provided to the arms may produce training effects, thereby altering arm swing expression.

Keywords

locomotion; arm swing; stepping; plasticity; motor control; spinal cord injury

Introduction

Arm swing is a natural feature of human locomotion. Although walking can be accomplished without arm swing, coordinated arm movement naturally emerges in neurologically-intact individuals.¹ Though the precise role of walking-related arm swing is unknown, possible benefits include reductions in center of mass vertical excursions and vertical ground reaction moments and increases in metabolic efficiency.² Regardless of its role, arm swing likely is supported by neuronal circuitry linking spinal centers innervating the arms and legs³ and may be guided by cortical control.⁴

Electrophysiological studies investigating interlimb reflexes suggest that pathways which connect spinal cord areas innervating the upper and lower extremities exist in neurologically-intact humans and some humans with spinal cord injury (SCI).^{5, 6} An important first step in elucidating interactions between the arms and the legs during walking and the functional role of associated pathways is to understand the impact of spinal injury on walking-related arm swing and determine the influences of environment and/or experience on arm swing post-injury. Additionally, determining whether arm swing may be associated with clinical scores reflecting volitional strength and/or assistance required for walking may provide insight into ways to predict the presence of, or identify the potential for recovering, arm swing. Since a primary goal after SCI often is to retrain walking, it also is important to determine whether current rehabilitation approaches affect upper extremity movement during walking. These vantages are of particular interest based on our understanding that 1) repetitive sensory experiences can shape motor learning and enhance activity-dependent neural plasticity and 2) augmenting sensory input provided to the spinal cord when descending supraspinal input is diminished can enhance task-specific training outcomes.⁷

Additionally, some evidence suggests integration of the upper extremities can influence lower extremity motor output.⁸⁻¹⁰ Therefore, rehabilitation and/or daily activities may impact walking-related arm movement, which in turn, could influence walking recovery after SCI. The purpose of this study was to determine: 1) the presence of walking-related arm swing after motor incomplete SCI (iSCI), 2) factors associated with arm swing (i.e. neurological level of impairment, voluntary leg and arm strength, assistive device, and walking independence) and 3) whether locomotor training (LT) which provides intense stepping practice in a treadmill environment with partial body weight support (BWS) and manual assistance without the constraint of assistive devices may influence arm swing.

Materials and Methods

Subjects

Thirty individuals (mean \pm standard deviation, 40 ± 14 yrs, 23 ± 18 mos post-injury, 8 females) with motor iSCI (American Spinal Injury Association Impairment Scale (AIS)¹¹ grade C/D, as defined by the International Standards for Neurological Classifications of SCI (ISNCSCI) with neurological level of impairment at or below C4) were recruited from a sample of convenience. Enrolled participants were blinded to the study's purpose. Clinical scores (reported as mean \pm standard deviation/median (interquartile (IQ) range)) from the sample were: $41 \pm 9/43$ (36–50), ISNCSCI upper extremity motor scores (UEMS, max = 50);¹¹ $36 \pm 10/39$ (31–44), ISNCSCI lower extremity motor scores (LEMS, max = 50)¹¹; and $12 \pm 5/13$ (8–15), Walking Index for SCI II (WISCI II, max = 20) scores.¹² All participants were able to flex their shoulders at least 90°. Institutional and federal regulations concerning ethical use of human volunteers were followed.

Arm Movement

Some devices like crutches and canes allow arm swing during stepping, while other devices such as walkers do not. To remove the confound of arm loading, arm movement was evaluated in the treadmill environment with vertical BWS. Since some subjects could not step independently, manual assistance at the legs was provided as needed, and speed was adjusted to create a permissive stepping environment enabling individuals to step on the treadmill without their usual assistive devices. Instructional cues relating to arm movement were not provided during any walking evaluations. Arm movement was defined as present (versus absent) when gleno-humeral movement in the sagittal plane was detected and dissociated from upper trunk and shoulder rotation. Four individuals dichotomized arm movement across participants using 3-dimensional joint kinematics (Vicon; Oxford, UK), when available. Not all enrolled participants underwent angular kinematic evaluation, and therefore, some assessments of arm movement were conducted via frame-by-frame video analysis. Bias was minimized by blinding assessors from participant identity and demographics.

Clinical Assessments

Neurological level of impairment and upper and lower extremity voluntary strength were evaluated using the ISNCSCI AIS.¹¹ Individuals were categorized as full-time walkers, part-time walkers, or non-walkers (wheelchair users). For individuals classified as part- or

full-time walkers, the device used most frequently for walking at home or in the community was determined. Walking independence was assessed using the WISCI II¹² which identifies the need for assistive devices, bracing, and manual assistance during a short overground walk. Licensed physical therapists completed clinical assessments.

Locomotor Training (LT)

Twenty-one of the thirty individuals (39 ± 15 yrs, 23 ± 19 mos post-injury, 7 females) also were enrolled in a 9 week manual-assisted LT program (5x/wk).¹³ Clinical scores from these 21 individuals were: $39 \pm 9/38$ (35–48), UEMS;¹¹ $35 \pm 10/37$ (29–44), LEMS;¹¹ and $11 \pm 5/12$ (8–14), WISCI II.¹² Briefly, training consisted of 20–30 minutes of treadmill stepping practice using partial BWS. Trainers provided manual assistance at the pelvis, trunk, and lower extremities, as needed. Upright posture, loading through the lower extremities, appropriate weight shift, and stepping coordination were emphasized to approximate normal walking speeds during stepping practice (0.8–1.2 m/s). As independence increased, trainers reduced their assistance, BWS was decreased, and/or treadmill speeds were increased. During LT, parallel bars were not used; and coordinated, reciprocal arm movement was encouraged. Subjects held horizontal poles moved by trainers and/or were given verbal cues to promote arm swing during some sessions. Subjects were weaned from assistance as independent arm swing emerged. Following the LT program, arm movement was re-assessed on the treadmill.

Statistical Analyses

Data were analyzed with SPSS v16.0 (Chicago, IL) and Minitab v15 (State College, PA). Two binomial proportions tests were used to compare the presence of arm swing based on cervical versus thoracic neurological levels of impairment and the customary assistive device used for community ambulation (wheelchairs, rolling platform walkers, or rolling walkers which restrict arm swing versus crutches, canes, or no assistive devices which allow arm swing). Mann-Whitney U tests were used to compare 1) UEMS,¹¹ 2) LEMS,¹¹ and 3) WISCI-II scores¹² among groups with and without arm swing. To determine the effects of LT on individuals without arm swing, pre- versus post-training analyses were conducted on the 16 individuals without arm swing at baseline (pre-LT). Exact p-values using a binomial distribution were obtained with the McNemar test. Lastly, among participants who did not exhibit arm swing at baseline, a Wilcoxon-signed rank test examined whether arm swing observed post-LT may be associated with changes in customary assistive devices used for community ambulation pre- versus post-LT. Assistive devices were ranked based on the amount of assistance provided. The median of the ranks pre-versus post-LT were compared separately for those individuals that did and did not recover arm swing post-LT.

Results

Arm swing was absent during treadmill-based stepping in 60% of the individuals with iSCI

Of the 30 individuals with iSCI evaluated prior to LT, only 12/30 (40%) demonstrated walking-related arm movements. Though this natural feature of locomotion typically is present in the neurologically-intact population at walking speeds ranging from 0.2 m/s and beyond,¹ it was absent in 18/30 (60%) of our iSCI participant pool. In individuals not

demonstrating arm movement, the arms often remained flexed at the elbows in a rigid and stationary position during stepping (Figure 1).

Associations with walking-related arm movement

The difference between arm swing presence among individuals with cervical versus thoracic neurological levels of impairment was -12.5% (Table 1, $p=0.58$, 95% confidence interval (CI) -57% to 32%) and not statistically significant. In addition, differences in UEMS (Mann Whitney U, $p=0.19$) were not detected among individuals with and without arm swing. However, differences in LEMS were detected among these two groups (Mann Whitney U, $p=0.048$).

The difference between the presence of arm swing among individuals using assistive devices promoting versus restricting reciprocal arm swing was significant at -38% (Table 2, $p=0.04$, 95% CI -74% to -2%). This suggests individuals using no device, a cane, or crutches were more likely to demonstrate arm movement during treadmill stepping than individuals who use wheelchairs, rolling platform walkers, or walkers for community ambulation. Differences in WISCI-II scores also were detected among individuals with and without arm swing (Mann Whitney U, $p=0.008$).

Pre- versus post-differences in arm swing suggest LT may influence arm movement during stepping

Prior to LT, only 5/21 individuals demonstrated arm swing during stepping and 16/21 did not. Of these 16 individuals initially lacking arm swing pre-LT, 8 independently integrated arm swing post-LT. Statistical analyses assessing pre- versus post-LT differences targeted these 16 individuals that did not incorporate arm swing pre-LT. Pre- versus post-LT differences in proportions of individuals eliciting arm swing were significant at 38% (Table 3, $p=0.008$, 95% CI 10% to 38%). Only 3/8 individuals that did not develop arm swing post-LT changed to a less restrictive device, compared to 5/8 individuals that developed arm swing post-LT (Table 4). Medians based on ranks reflecting the amount of assistance assistive devices provide pre- versus post-LT were compared. Median differences for those not integrating arm swing following LT were not significantly different (Wilcoxon signed rank test, $p=0.10$); while median differences were statistically significant for individuals integrating arm swing post-LT (Wilcoxon signed rank test, $p=0.04$).

Discussion

Arm swing during stepping was altered in some individuals after motor iSCI

Arm swing during treadmill stepping was completely absent in a majority (60%) of participants with iSCI. To our knowledge, this study is the first to examine arm swing in individuals with iSCI. Previous reports indicate arm swing often is diminished or absent in individuals with other types of central nervous system damage, such as stroke or Parkinson's disease.^{14, 15} Collectively, these results suggest arm swing may be influenced, *at least in part*, by diverse levels (supraspinal versus spinal) of the neural axis.

Arm swing was associated with LEMS but not UEMS or neurological levels of impairment

Interestingly, significant differences among individuals with and without arm swing were detected in LEMS, but not UEMS or neurological level of impairment (cervical/thoracic). While walking-related arm swing can be influenced by the cortex,⁴ it is not considered a voluntary behavior and therefore may be unaffected by upper extremity strength. More likely, arm swing is influenced by spinal cord areas innervating the arms and legs and the functional integrity of the connecting pathways. Typically, those with a higher LEMS have greater neural sparing which might translate to less disruption of intraspinal connections between these spinal areas. Alternatively, individuals with higher LEMSs may be higher functioning walkers, and therefore more likely to demonstrate walking-related arm movement.

Activity-dependent plasticity can affect gait-related arm movement following iSCI

Repetitive sensory experiences can shape motor learning and enhance activity-dependent plasticity in the neuromuscular system.⁷ Significant associations between arm movement and both WISCI-II scores and assistive devices were detected. This suggests that the experience of load-bearing through the upper extremities, which often is encouraged by assistive devices used during rehabilitation and activities related to daily living, may promote or contribute to the absence of walking-related arm swing post-injury. Moreover, some LT programs have utilized parallel bars.^{13, 16} In these instances, weight again is loaded through the upper extremities,¹⁷ thereby diminishing arm swing and altering the input integrated and interpreted by the spinal cord. Alternatively, during LT, a harness and overhead body weight support system can provide vertical unloading through the trunk, giving the arms freedom to move. In this study, arm swing was practiced during the course of LT with partial BWS, thereby altering the daily experiences provided to the arms. As a result, the coordinated arm swing experience during stepping practice contributed to the ensemble of sensorimotor cues promoting independent arm swing on the treadmill. It is unknown whether arm swing would have emerged without this practice. Regardless, training experience provided to the arms through specific use or practice is likely to have an impact at the neural level, which may manifest behaviorally as a presence or lack of arm swing, depending on the specific experience.

Training walking-related arm swing post-iSCI may provide a biomechanical advantage during stepping and locomotor training

Reports in the literature suggest arm swing may confer a biomechanical advantage during walking. In particular, arm swing appears to contribute to maintaining postural control and stability, independent of neural control, by reducing the reaction moment about the vertical axis of the foot.^{18,19} Furthermore, arm swing has been described as movement which is powered predominately by the legs during walking, via elastic linkages between the legs, trunk, and arms.²⁰ These elastic interactions are thought to exist in order to help reduce and maintain a reasonable amount of torso and head rotation with the arms acting as mass dampers.²⁰ Therefore, it is possible that arm swing is altered following iSCI, in part, because of biomechanical changes in walking that may occur after injury. Regardless of the basis for arm swing and whether it is biomechanically and/or neurally based, the

biomechanical advantages that appear to result from walking-related arm swing suggest that the proprioceptive input provided to the arms during swing may be very important and relevant to walking recovery and retraining post-iSCI.

Sensorimotor experiences of the arms may play an important role in enhancing locomotor function

Specific experiences achieved by incorporating arm swing practice during interventions like LT may increase the likelihood that arm swing will emerge during walking recovery. However, integrating arm swing may promote greater efficiency during walking. For example, preventing arm swing or swinging the arms in an opposite-to-normal phase requires 12% and 26% more metabolic energy, respectively, compared to swinging the arms naturally during locomotion.² Therefore, incorporating speed-appropriate patterns of arm swing during gait retraining may reduce energy expenditure during walking. In addition, active integration of the arms during a task in which the lower extremities move rhythmically and reciprocally can enhance muscle activity in the legs.^{8-10, 15, 16, 21} In healthy controls and individuals with Parkinson's disease or stroke, incorporating arm swing during recumbent stepping or walking can alter or improve lower extremity muscle activation during stepping.^{8, 10, 15} Additionally, Behrman and Harkema (2000) suggest integrating arm swing during LT may improve lower extremity muscle recruitment following iSCI.²¹ This concept also is supported by Visintin and Barbeau's work (1994). Eliminating load-bearing through the arms and increasing loading through the legs during treadmill stepping with partial BWS elicited more rhythmical, symmetrical, and reciprocal gait patterns with increased lower extremity muscle activation.¹⁶ While integrating upper extremity effort during recumbent stepping did not increase lower limb muscle activation in individuals with iSCI,²² incorporating passive arm movements during passively imposed leg movements increased plantarflexor activity throughout the backward swing phase using a stand gliding apparatus.⁹ Thus, task-specificity of the sensorimotor experience (e.g. upright load-bearing) may be critical for arm movements to facilitate leg activation.

Limitations and Future Directions

While no differences in arm swing presence were observed based on neurological levels of impairment (cervical/thoracic), only 6/30 individuals assessed had thoracic injuries. A sample of more evenly distributed groups may be warranted to verify these results and their interpretation. In addition, the extent of tissue damage in the spinal cord may be an important consideration and one potential confound. Since all individuals in this study had incomplete injuries, areas where propriospinal fibers project may have been disrupted differentially. Furthermore, investigating arm swing in individuals with injuries between, above, or below cervical and lumbar enlargements might be particularly interesting, based on Dietz's report (1999) suggesting individuals with more rostral lesions show more normal lower extremity locomotor patterns.²³

Conclusion

The presence of walking-related arm swing appears altered following iSCI. While some individuals in this study demonstrated arm swing during treadmill stepping; pre-LT, the majority did not. One factor which may contribute to the presence of arm swing after injury

is the exposure to specific experiences that vary arm position, load-bearing, and use during walking. In this study, we observed associations between the presence of arm swing and assistive device use and locomotor training. This study illustrates the differential impact that injury, experience, and practice may have on walking-related arm movement. Rehabilitation efforts therefore may benefit from highlighting arm swing as an important component or consideration following spinal cord injury.

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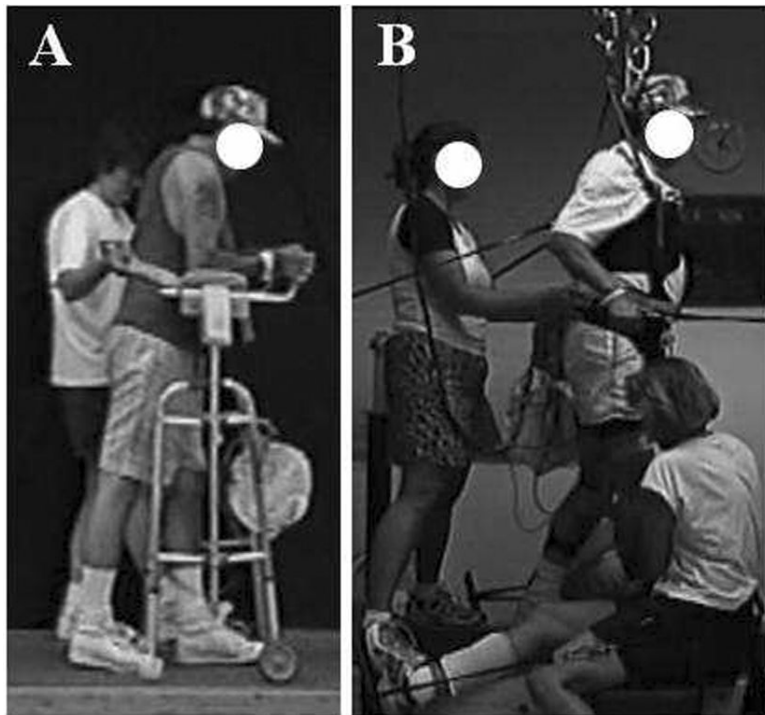


Figure 1. Arm movement during stepping

Individuals walking with a rolling platform walker typically walk with their arms flexed at the elbow and weight distributed through their upper extremities. This decreases the amount of body weight loaded through their lower extremities (A). Placing individuals on the treadmill with partial BWS (a condition in which their assistive device can be removed), however, provides the arms with an opportunity to move more naturally. Despite this, the arms of some individuals remain flexed in a fixed position and do not move or swing during manually-assisted stepping, regardless of walking speed (B).

Table 1

Presence of arm movement during walking was not associated with cervical versus thoracic neurological levels of impairment.

	Cervical (n=24)	Thoracic (n=6)
Arm Swing	9/24 37%	3/6 50%
No Arm Swing	15/24 63%	3/6 50%

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Associations between arm swing and the primary type of assistive device used for community ambulation following iSCI. Assistive devices were grouped by those which promote reciprocal arm swing during stepping (columns 5–7) versus those that do not permit reciprocal arm swing (columns 2–4).

Table 2

	All Devices (n=30)	WC (n=8)	RPW (n=5)	RW (n=8)	Cane (n=4)	Crutches (n=1)	No Device (n=4)
Arm Swing	12/30 40%	1/8 12%	0/2 0%	5/11 45%	2/4 50%	0/1 0%	4/4 100%
			6/21 = 29%			6/9 = 67%	
No Arm Swing	18/30 60%	7/8 88%	2/2 100%	6/11 55%	2/4 50%	1/1 100%	0/4 0%
			15/21 = 71%			3/9 = 33%	

WC = wheelchair, RPW = rolling platform walker, RW = rolling walker.

Table 3

The presence of walking-related arm movement pre- versus post-LT.

	Arm Swing	Post-LT		Totals
		Yes	No	
Pre-LT	Yes	5	0	5
	No	8	8	16
	Totals	13	8	21

Table 4

Pre- and post-LT device use related to arm swing. Individuals who did not demonstrate arm swing either pre-LT or post-LT showed few changes in device use. However, when arm swing emerged post-LT, most individuals switched to a less restrictive device.

	Device Pre-LT	Device Post-LT
No Arm Swing Pre-LT; No Arm Swing Post-LT	WC	WC
	RPW	RW
	RW	Crutches
	WC	WC
	WC	RW
	WC	WC
	RW	RW
	WC	WC
No Arm Swing Pre-LT; Arm Swing Post-LT	Cane	No Device
	WC	WC
	RPW	Crutches
	RW	Cane
	Cane	No Device
	Crutches	Cane
	RW	RW
	RW	RW

WC = wheelchair, RPW = rolling platform walker, RW = rolling walker.

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