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## Research Article

# Effects of robotic-assisted gait training on the central vascular health of individuals with spinal cord injury: A pilot study

James Faulkner<sup>1</sup>, Louis Martinelli<sup>2</sup>, Kirsty Cook<sup>2</sup>, Lee Stoner<sup>3</sup>,  
Helen Ryan-Stewart <sup>1</sup>, Eloise Paine<sup>1</sup>, Helen Hobbs<sup>2</sup>, Danielle Lambrick<sup>4</sup>

<sup>1</sup>Department of Sport, Exercise and Health, University of Winchester, Winchester, UK, <sup>2</sup>Hobbs Rehabilitation, Winchester, UK, <sup>3</sup>School of Sport and Exercise Science, University of North Carolina, Chapel Hill, North Carolina, USA, <sup>4</sup>Faculty of Health Sciences, University of Southampton, Southampton, UK

**Objective:** To investigate the effect of a short-term, robotic-assisted (exoskeleton) gait training (RGT) program on central and peripheral hemodynamic measures in patients with spinal cord injury (SCI).

**Design:** Parallel group, non-randomized trial with before (baseline) and after (follow-up) assessments.

**Setting:** Single-center, community-based neuro-physiotherapy practice.

**Participants:** Twelve individuals with SCI (ASI A to C).

**Interventions:** Participants completed either a 5-day RGT program plus physiotherapy ( $n = 6$ ), or a usual care physiotherapy only program (control group;  $n = 6$ ). The RGT program consisted of daily 60-min physiotherapy and 90-min of RGT. Outcome measures were measured before and after the rehabilitation program.

**Main outcome measure(s):** The primary outcome measure was arterial wave reflection (Augmentation index [Alx]), with central and peripheral blood pressures also reported. Data are presented as mean (SD) and effect sizes (partial eta squared;  $\eta_p^2$ ).

**Results:** There was a significant reduction in Alx ( $30 \pm 18$ – $21 \pm 15\%$ ;  $\eta_p^2 = 0.75$ ) and mean arterial pressure ( $89 \pm 11$ – $82 \pm 10$  mmHg;  $\eta_p^2 = 0.47$ ) following completion of the RGT program (both  $P < 0.05$ ). There were no changes in these measures for the control group. Although not significantly different, medium to large effects were observed in favor of RGT for all other central and peripheral measures ( $\eta_p^2 = 0.06$ – $0.21$ ), except for heart rate and pulse pressure ( $\eta_p^2 < 0.04$ ).

**Conclusions:** RGT using an exoskeleton is a promising therapy for improving cardiovascular health in patients with SCI. Specifically, this study indicates decreased arterial wave reflection and supports the need for larger randomized controlled trials.

**Trial Registration:** Clinical trials Registry (<https://clinicaltrials.gov/>; NCT03611803).

**Keywords:** SCI, Blood pressure, Cardiovascular health, Rehabilitation, Robotics

## Introduction

Individuals with spinal cord injury (SCI) have an accelerated trajectory of aging in the cardiovascular system compared with same-age individuals in the general population,<sup>1</sup> and accordingly, have a higher rate of cardiovascular mortality.<sup>2</sup> For example, SCI is significantly associated with an increased risk of heart disease (odds ratio = 2.72) and stroke (odds ratio = 3.72).<sup>3</sup> This is at least partially attributed to their impaired blood

pressure regulation as a consequence of the autonomic nervous system dysfunction, physical inactivity and increased sedentary time. As such, there is a pressing need to identify practical strategies for increasing physical activity and decreasing sedentary time in people with SCI.<sup>4</sup>

Robotic-assisted gait training (RGT) is used in the rehabilitation of patients with SCI, and may be a viable option to improve functional and health outcomes, and independence, in this population group. Task-specific stepping practice enhances the afferent feedback associated with normal locomotion and can

Correspondence to: James Faulkner, Reader in Exercise Physiology, Department of Sport, Exercise and Health, University of Winchester, Winchester, SO22 4NR, UK. Email: James.Faulkner@winchester.ac.uk

induce plasticity in the involved motor centers.<sup>5,6</sup> Robotic powered exoskeletons are wearable robotic units that power a system of motors, pneumatics, levers, or hydraulics to restore locomotion through RGT programs.<sup>7,8</sup> A systematic review and meta-analysis of 14 exoskeleton studies, typically including RGT programs that consisted of training sessions three times per week, 60–120 min per session, for 1–24 weeks, demonstrated that 76% of patients were able to ambulate with no physical assistance on completion of an exoskeleton program.<sup>8</sup> The physiological demand of such exoskeleton-assisted walking programs are comparable to self-reported exertion of an able-bodied person walking at 3 miles per hour and can elicit improvements in spasticity, without any serious adverse events.<sup>8,9</sup> Robotic exoskeletons may decrease seated time, increase standing and walking time,<sup>10,11</sup> thus, potentially ameliorating several of the chronic health-related consequences that negatively impact this population.<sup>12,13</sup>

As RGT enables practitioners to increase the intensity and total duration of physical activity whilst maintaining a physiological gait pattern,<sup>14</sup> there may be a significant benefit for people with SCI to manage their risk of cardiovascular disease (CVD). This may be evident if an individual with SCI has regular and continued access to such technology. However, there is a paucity of research which has considered the vascular benefit of implementing RGT for people with SCI as most research focuses on outcome measures such as gait velocity, gait distance, leg strength, balance, and spasticity.<sup>14</sup> Furthermore, while this technology may be practical in terms of application in medical centers and community settings,<sup>7</sup> the cost is currently prohibitive. Thus, prior to advocating resource intensive longitudinal randomized control trials, there is a need for short-term trials using established measures of cardiovascular health.<sup>15</sup>

The measurement of central hemodynamic parameters, including central systolic blood pressure (cSBP) and arterial wave reflection (augmentation index, AIx) have the potential to provide clinicians with important diagnostic and prognostic information beyond traditional blood pressure (BP) readings.<sup>16</sup> Central BP has been reported to be a stronger determinant of cardiovascular events than peripheral BP,<sup>17</sup> while AIx, a measure used to infer the degree of systemic arterial wave reflection, has been demonstrated to predict future cardiovascular events and all-cause mortality independent of peripheral or central BPs.<sup>17,18</sup> These parameters can be obtained using ‘Pulse Wave Analysis’ (PWA), a valid and reliable noninvasive procedure.<sup>16,19–22</sup> A recent study demonstrated that

individuals with SCI who have high cord lesions have more severe cardiovascular autonomic disruption, leading to orthostatic BP dysregulation and physical inactivity, which appear to contribute independently to increased arterial stiffness in these individuals.<sup>23</sup> Despite the importance of measuring central BP and AIx, peripheral BP is widely used in clinical and non-clinical settings as a measure of vascular health.

The purpose of this pilot study was to assess the effect of a RGT (exoskeleton) program on central and peripheral hemodynamic markers in people with SCI. It was hypothesized that improvements in vascular health would be evident through a reduction in central and peripheral BP, and AIx, in people with SCI who used the exoskeleton.

## Methods

### Participants

A convenience sample of 12 individuals with SCI, who were actively seeking neuro-physiotherapy from a single center (Hobbs Rehabilitation, Winchester, UK), participated in the study. Participant demographics, including age, height, weight, SCI etiology and type, time since SCI, and distance traveled to participate in the research study, were collected from a health history questionnaire (Table 1). Due to the pilot nature of the study, a quasi-experimental design was implemented whereby the first six participants were assigned to the RGT program, and the remaining six to the control (Con) group. Participants using the RGT exoskeleton (Ekso bionics, USA) met the manufacturer’s guidelines with regards to inclusion criteria for weight (<100 kg),

**Table 1 Participant demographics.**

	RGT	Con
Participants (n)	6	6
Sex		
Male	3	3
Female	3	3
Age (y) <sup>a</sup>	30 (13)	38 (17)
Height (m) <sup>a</sup>	1.75 (0.09)	1.76 (0.11)
Weight (kg) <sup>a</sup>	63.8 (17.4)	62.8 (18.4)
Etiology		
Traumatic	6	6
Non-traumatic	0	0
Type		
ASI A	4	2
ASI B	1	2
ASI C	1	2
ASI D	0	0
Time since SCI (y) <sup>a</sup>	2.7 (1.3)	3.6 (2.5)
Distance (km) <sup>a*</sup>	95 (30)	71 (56)

ASI, American Spinal Cord Association Impairment Scale; Con, Control group; RGT, Robotic-assisted gait training; SCI, Spinal cord injury.

<sup>a</sup>Mean (standard deviation).

\*This refers to the distance between the participants’ home and the neuro-physiotherapy center which conducted the study.

height (between 1.57 and 1.93 m), and range of motion (bilateral hip flexion  $110^\circ$ ,  $\leq 12^\circ$  knee contracture, neutral dorsiflexion). All participants were standing at least three times a week with therapist support and classified, according to the American Spinal Injury Association Impairment Scale (ASI) scale, as either ASI A (Complete SCI), ASI B (Sensory incomplete SCI), ASI C (Motor incomplete SCI) or ASI D (Motor incomplete SCI). Participants were excluded if they had uncontrolled high levels of muscle spasticity (Modified Ashworth Scale  $\geq 4$ ), high blood pressure ( $>160/90$  mmHg), and/or if there were clinically diagnosed concerns with their bone density (e.g. osteoporosis, etc.). Institutional ethical approval was granted and the study was registered with the Clinical trials Registry (<https://clinicaltrials.gov/>; Trial Registration Number: NCT03611803). Written informed consent was obtained prior to participation.

### Procedures

The measurement procedures were discussed with all eligible participants prior to the start of the study. All participants completed an identical baseline (day 1) and follow-up (day 5) vascular health assessment using PWA at a neuro-physiotherapy practice, between the hours of 11:00 and 12:00 and following a minimum 3-h fast. Between the baseline and follow-up assessments, participants in the RGT group attended the neuro-physiotherapy practice on five consecutive days for robotic-assisted gait training using the exoskeleton.

### Pulse wave analysis

All participants were instructed to refrain from: (i) supplement intake during the morning of the baseline and follow-up assessments, (ii) strenuous rehabilitation exercises within 24 h preceding baseline, and (iii) alcohol consumption 24 h prior to both PWA assessment sessions. At baseline and follow-up assessments, and following 20 min undisturbed, supine rest, oscillometric pressure waveforms were recorded by a single operator on the left upper arm using a brachial blood pressure cuff (SphygmoCor XCEL device, AtCor Medical, Sydney, Australia), in accordance with standard manufacturer's guidelines.<sup>24</sup> Each measurement cycle lasted approximately 60 s, consisting of a brachial BP recording and then a 10 s subsystolic recording. The merging point (the inflection point) of the forward and reflected waves was identical on the derived aortic pressure waveform. Augmentation pressure is defined as the maximum systolic pressure minus the pressure of the inflection point. The AIx is defined as the augmentation pressure expressed as a percentage of central pulse

pressure. AIx is influenced by heart rate, and thus an index corrected for heart rate at 75 bpm (AIx75) was also calculated. Two measurements were taken, with a minimum 3 min interval. If blood pressure differed by more than 5 mmHg or AIx by  $> 4\%$ , a third recording was taken and the closest two recordings were averaged in line with recommendations.<sup>24,25</sup>

### RGT exoskeleton training program

On completion of the baseline assessment all participants involved in the RGT exoskeleton program completed a 60 min conventional therapy session (morning) and a 90 min RGT session (afternoon) using a wearable exoskeleton, on five consecutive days. The design of the program (conventional therapy in the morning, RGT in the afternoon) was standardized for all RGT participants. As demonstrated in Table 1, patients often travel long distances to receive therapy from neuro-physiotherapy practices. Accordingly, for logistical but also therapeutic reasons, Hobbs Rehabilitation (neuro-physiotherapy practice involved in this study) provides patients with the opportunity to engage in intense, short-duration therapy programs. The 90 min RGT sessions incorporated the time required to set-up the exoskeleton, and all exercise and rest periods. The 60 min conventional therapy sessions were completed by one physiotherapist and included a variety of treatment techniques depending on the needs of the patient. This typically included lower limb muscle lengthening, core stability and functional sitting balance exercises.

The 90 min RGT sessions were completed by two physiotherapists and used various settings on the exoskeleton. Patients would commence their program on day 1 with the 'First Step' setting where the therapist dictated the steps taken. Following optimal weight transfer, which was determined by a therapist who had  $> 4$  years experience using the exoskeleton, the 'ProStep+ bilateral adapt' setting was administered. This setting allows the participant to control their steps by transferring their body weight. The therapist would ensure progressive overload by altering the following settings to allow the exoskeleton to improve each participant's gait pattern; including degree of leg extension, stride length, step height, and step speed. A wheeled frame was initially used at the start of the day 1 session, but all patients progressed to use crutches by the end of first days session and were used for all remaining RGT training sessions. Participants were allowed rest periods at their request. The participants 'Up Time', 'Walk Time' and number of 'Steps' per session were recorded, as well as the minimum level of motor assistance provided by the exoskeleton.

### Control group

Between baseline and follow-up assessments, participants in the Con group received a daily 60 min conventional physiotherapy session, similar to that undertaken by the RGT group, and a daily 60 min home-based rehabilitation exercise session. This included 30 min of static standing using a frame, and 30 min of stretches (*i.e.* hip flexor exercises), sitting balance and core-stability exercises (e.g. targeting transverse abdominis), with relevant rest periods incorporated within this time frame.

### Statistics

A series of two-way ANOVAs; Condition (RGT, Con)  $\times$  Time (Baseline, Follow-up) were used to assess changes in PWA (including cSBP, central diastolic blood pressure [cDBP], pulse pressure [PP], peripheral systolic blood pressure [SBP], peripheral diastolic blood pressure [DBP], mean arterial pressure  $\langle$ map $\rangle$ , heart rate [HR], Aix, and Aix75). Data are presented as Mean (SD) with 95% confidence intervals (CI) where necessary. Effect sizes are reported to describe the importance of the relevant findings in practical terms. Partial eta squared ( $\eta_p^2$ ) was used as a measure of effect size, with .0099, .0588 and .1379 representing a small, medium and large effect, respectively. Paired sample *t*-tests were used to assess the participants' time spent upright

and walking in the exoskeleton, the number of steps recorded and the minimum amount of motor assistance provided by the exoskeleton on completion of the first (day 1) and last day (day 5) to the RGT program. Cohen's *d* was used as a measure of effect size for these analyses, with 0.2, 0.5 and 0.8 representing a small, medium and large effect, respectively.<sup>26</sup> Statistical significance was set at  $P = 0.05$ . All analysis was undertaken using SPSS Version 24.0.

### Results

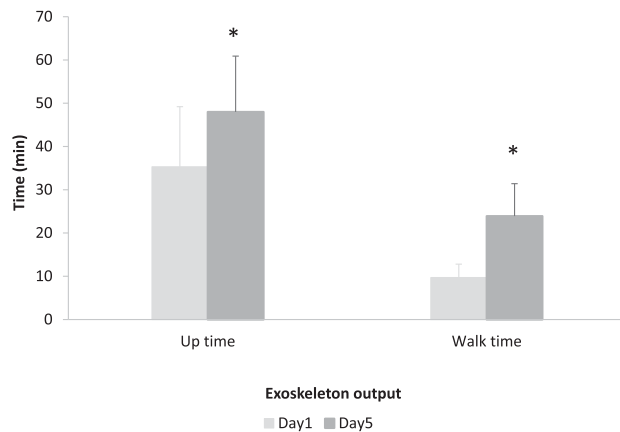
The mean (SD) peripheral and central hemodynamic values can be observed in Table 2. Significant Condition  $\times$  Time interactions were observed for Aix ( $\eta_p^2 = 0.74$ ), Aix75 ( $\eta_p^2 = 0.67$ ), AP ( $\eta_p^2 = 0.44$ ), and MAP ( $\eta_p^2 = 0.47$ ) (all  $P < 0.05$ ), with cDBP approaching statistical significance ( $\eta_p^2 = 0.35$ ). Each of these outcomes remained constant for Con, but decreased (improved) between baseline and follow-up assessments for RGT (Mean [95%CI]; Aix  $-9\%$  [ $-12.2$  to  $-5.8$ ]; Aix75  $-7\%$  [ $-9.8$  to  $-4.2$ ]; AP  $-6\%$  [ $-13.1$  to  $-0.7$ ]; MAP  $-7$  mmHg [ $-10.8$  to  $-2.7$ ]). There were no interactions for all other peripheral and central hemodynamic variables (all  $P > 0.05$ ) but, with the exception of HR and PP, medium to large effect sizes were observed ( $\eta_p^2 = 0.06-0.21$ ).

**Table 2 Mean and SD of PWA indices for individuals with SCI in RGT ( $n = 6$ ) and Con ( $n = 6$ ).**

		RGT ( $n = 6$ )		Con ( $n = 6$ )		<i>P</i>	$\eta_p^2$
		Baseline	Follow-up	Baseline	Follow-up		
MAP (mmHg)	X	89	82	86	87	*0.029	0.47
	SD	11	10	17	20		
SBP (mmHg)	X	125	118	130	131	0.157	0.21
	SD	19	10	10	11		
DBP (mmHg)	X	71	66	76	76	0.162	0.21
	SD	8	8	9	13		
PP (mmHg)	X	55	53	54	55	0.577	0.04
	SD	12	3	8	9		
cSBP (mmHg)	X	117	110	118	120	0.135	0.21
	SD	17	11	9	9		
cDBP (mmHg)	X	72	67	77	78	0.055	0.35
	SD	8	8	9	11		
cPP (mmHg)	X	51	48	41	42	0.461	0.06
	SD	21	19	7	6		
HR (b·min <sup>-1</sup> )	X	55	56	67	70	0.714	0.02
	SD	13	10	16	19		
AP (%)	X	18	12	12	13	*0.050	0.44
	SD	16	8	7	6		
Aix (%)	X	30	21	31	33	*0.001	0.75
	SD	18	15	12	14		
Aix75 (%)	X	21	14	22	25	*0.002	0.67
	SD	18	14	12	13		

Aix, Augmentation index; AP, Augmentation pressure; cDBP, Central diastolic blood pressure; cSBP, Central systolic blood pressure; Con, Control group; DBP, Diastolic blood pressure; HR, Heart rate; MAP, mean arterial pressure; PP, Pulse pressure; RGT, Robotic-assisted gait training; SCI, Spinal cord injury; SBP, Systolic blood pressure.

\*Significant difference ( $P < .05$ ).



**Figure 1** Mean (SD) time spent upright and walking in the Exoskeleton at Day 1 and Day 5 to the program.

Mean time spent upright by the RGT group in the exoskeleton significantly increased from day 1 to day 5 (mean [SD]: 35 [14] vs. 48 [13] min per session;  $P < 0.05$ ;  $d = 0.95$ ; Fig. 1), as did the amount of time spent walking (10 [3] vs. 24 [8] min per session;  $P < 0.05$ ;  $d = 2.47$ ) and the number of steps taken in the exoskeleton (193 [47] vs. 523 [125] steps per session at day 1 and day 5, respectively;  $P < 0.01$ ;  $d = 3.51$ ). The minimum level of motor assistance provided by the exoskeleton decreased from 81 (1) % to 67 (5) % between day 1 and 5 of the program ( $P < 0.01$ ;  $d = 4.02$ ).

## Discussion

This study demonstrated that five days of consecutive RGT, which elicited an increase in time spent upright, walking and stepping whilst wearing the exoskeleton, can decrease (improve) arterial wave reflection (AIx) and MAP in individuals with SCI. These findings are particularly interesting when considering that RGT training program was of a short duration. The present study supports the need for further work to determine how this approach may be beneficial in a patients' long-term rehabilitation strategy.

The mean reduction in AIx of 9% is of significant value when considering that AIx has been demonstrated to predict future cardiovascular events and all-cause mortality, independent of peripheral or central BP.<sup>17,18</sup> Vlachopoulos and colleagues<sup>17</sup> demonstrated that a 10% absolute increase in central AIx is associated with a 32% increase in the risk of cardiovascular events and 38% increase in all-cause mortality. Despite our findings, the AIx reported at the baseline and follow-up assessments are widely dispersed. Accordingly, although the mean reduction in AIx is encouraging from less than one week of daily ambulatory robotic training, further research consideration is needed. Furthermore, the

present study also demonstrated favorable changes to cDBP and MAP, with mean decreases of 5 and 7 mmHg, respectively, observed for the RGT group. Although SBP is considered the strongest peripheral BP predictor of CVD risk,<sup>27,28</sup> in subjects aged 40 years and younger – a population which may be at a heightened risk of SCI – DBP has also been shown to be an important predictor of CVD risk.<sup>29</sup>

While a full mechanistic explanation is beyond the scope of this article, it may be speculated that the changes in peripheral vascular health may lead to a decreased central burden. In SCI, central hemodynamic control is impaired due to autonomic nervous system dysfunction. This is typically confounded by peripheral vascular dysfunction which will increase arterial wave reflection.<sup>30</sup> Previous research has shown that short-term exercise can improve peripheral vascular health, most likely due to an enhanced blood flow-induced shear stress.<sup>31</sup> This is a likely reason as to why our short-term RGT program could majorly benefit the vascular health of people with SCI.

## Clinical implications and future considerations

Robotic-assisted gait-training programs allow practitioners to increase the intensity and total duration of physical activity whilst maintaining a physiological gait pattern.<sup>14</sup> The present study demonstrated a mean increase in time spent upright (13 min; 46% increase), walking (14 min, 140% increase) and stepping (330 steps; 170% increase) between baseline and follow-up. These changes, although practitioner-driven at the start of the training program, are highly encouraging, particularly when considering that the mean time spent walking in the exoskeleton (24 min) nearly meets physical activity guidelines for ambulatory counterparts.<sup>32</sup> Long-term reductions in sedentary time and an increase in physical activity, which would help to increase blood flow shear stress,<sup>31</sup> could help prevent secondary complications associated with CVD for those with SCI.<sup>4</sup> When considering the prognostic value of central vascular health markers and the observed increases in physical activity, the present study demonstrates the importance of administering a short-duration, intense exoskeleton training program for people living with SCI. However, as we seek to establish the optimal rehabilitation recommendations for individuals with SCI, further research is needed with regards to how and when to implement short-term RGT programs into the longer-term rehabilitation strategy. It would be valuable to know the optimal training program (length, intensity and duration of RGT), and over what duration changes in arterial wave reflection

remain present following such a training program. Furthermore, when considering that ISCOS guidelines recommend that persons with SCI engage in at least 20 min of moderate to vigorous-intensity aerobic exercise three times per week to improve cardiorespiratory fitness,<sup>33</sup> further investigation into the cardiometabolic effect of RGT exoskeleton programs is warranted. It appears that such research studies would be applicable and feasible for individuals with SCI as the present study has shown that this population group are willing to travel long distances for the opportunity to engage in such rehabilitation programs (>100 km; Table 1). RGT programs have also been shown to impact positively on the users lives and may enhance their perceived well-being.<sup>34</sup> Nevertheless, the benefit of the RGT exoskeleton program in comparison to more widely available and less costly ambulatory assistance physiotherapy training programs needs to be assessed.

### Study limitations

Several limitations should be addressed in order to better contextualize the findings. Our preliminary findings are based on only six participants who engaged with the short-duration RGT exoskeleton program and who had different ASI classifications. A larger sample size, and the inclusion of a more specific ASI classification, such as the recruitment of individuals with only ASI 'A' or 'B' on the impairment scale, could make future findings more robust. Although we were able to quantify the time spent upright in the RGT group during the exoskeleton sessions, we were unable to obtain a similarly objective assessment during the home-based rehabilitation sessions for the control group. While it should also be recognized that SCI patients are difficult to recruit and require significant resources (therapist time, equipment, etc.), these preliminary data support the need for further funding and research. The inclusion of additional research centers would be necessary if seeking to recruit a larger study population, as our study population was recruited from a single center. When considering that our study assesses the acute effect of the proposed study intervention, the longitudinal effects on central hemodynamic parameters and arterial wave reflection, and the actual delivery of the training program (*i.e.* frequency of training sessions and/or duration of training program) warrants further consideration.

### Conclusion

The aim of this investigation was to determine the effect of a short-term robotic-assisted (exoskeleton) gait

training program on central and peripheral hemodynamic variables in people with SCI. Findings suggest that the training program, which elicited increases in time spent upright and walking whilst in an exoskeleton, can improve established measures of cardiovascular health in individuals with SCI. These findings support the need for future research, to examine whether such findings are evident in a RCT with a larger sample size, whereby outcome measures are assessed in both the short- and longer-term. Such studies may help demonstrate whether robotic-assisted training interventions are a practical option for improving cardiovascular health outcomes, morbidity and mortality in individuals with SCI.

### Suppliers

SphygmoCor XCEL device (AtCor Medical, Sydney, Australia)

Exoskeleton (Ekso bionics, USA)

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### ORCID

Helen Ryan-Stewart  <http://orcid.org/0000-0002-9059-912X>

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