USING A ROBOT-ASSISTED GAIT ORTHOSIS TO ASSESS LOWER LIMB PERFORMANCE IN NEUROREHABILITATION

Matthias J. Krenn(1,2), Bonnie E. Perry(2), John W. Chow(2), Keith E. Tansey (1,2,3,4)

(1) Department of Neurobiology and Anatomical Sciences, University of Mississippi Medical Center, Jackson, MS. (2) Center for Neuroscience and Neurological Recovery, Methodist Rehabilitation Center, Jackson, MS. (3) Department of Neurosurgery, University of Mississippi Medical Center, Jackson, MS.
(4) Spinal Cord Injury Medicine and Research Services, VA Medical Center, Jackson, MS

Corresponding Author: Matthias J. Krenn <mkrenn@umc.edu>

ABSTRACT

Robot-assisted gait devices provide intensive, repeated practice of task-specific movements. New developments of rehabilitation robots, as well as advances in technology, allow new forms to control and assess the performance of the lower limb during gait training. The Lokomat (Hocoma AG, Volketswil, Switzerland), an actuated exoskeleton over a treadmill with a body weight support system, controls leg movement towards a predefined trajectory of a physiological gait pattern by actuating hip and knee torques. Here, we investigated the combined effects of different Lokomat settings (guidance force, bodyweight support and treadmill speed) on the torque and kinematic profiles provided by the robotic device in neurologically intact adults (n=19). The results show that the outcome measures, namely hip/knee torques and deviation of the cyclogram from the desired trajectory, are significantly influenced by the settings. These intrinsic kinematic and torque measures during assisted treadmill walking provide real-time movement feedback about the participant's performance. Furthermore, in research and clinical applications, this monitoring can help to adapt and improve a therapy strategy and documents the rehabilitation progress.

Keywords: robot-assisted walking, Lokomat, kinematic assessment, guidance force, impedance control.

INTRODUCTION

Robot-assisted gait devices provide intensive, repeated practice of task-specific movements that have been shown to improve walking in patients with neurological disorders [1]–[4]. The main purpose of robotic rehabilitation devices is not only to achieve a more intense gait training [5] but also to allow an objective measure of patient performance compared to manually assisted treadmill gait training [4].

One such device is the Lokomat (Hocoma AG, Volketswil, Switzerland) which consists of an exoskeleton with integrated computer-controlled linear actuators at each hip and knee joint, a body weight support system, and a treadmill (Fig. 1, A). This rehabilitation device controls leg movement towards a predefined trajectory of a physiological gait pattern by controlling the hip and knee joint torques of the exoskeleton [6]. A cascaded control system (Fig. 1, B) integrates a first-order impedance controller (proportional- derivative, PD) for angle deviations and second-order proportional (P) torque controller. The control coefficients can be directly modified by the guidance force (GF) setting which is a crucial parameter of Lokomat settings. GF changes the stiffness of the controllers and allows more or less deviation from the desired leg trajectory. Treadmill speed (SP) and body weight support (BWS) may also influence sensory feedback and the intensity of the training, which may affect the ability of a participant to comply.

Here, we investigated the combined effects of Lokomat settings (GF, SP, BWS) on the robotic-assistance torque profiles and the deviation between the desired and actual trajectory in an able-bodied study group. The study presents how different Lokomat configurations alter the gait kinematics and robotic torques in order to establish baseline patterns against which subjects with neurological disorders can be compared.

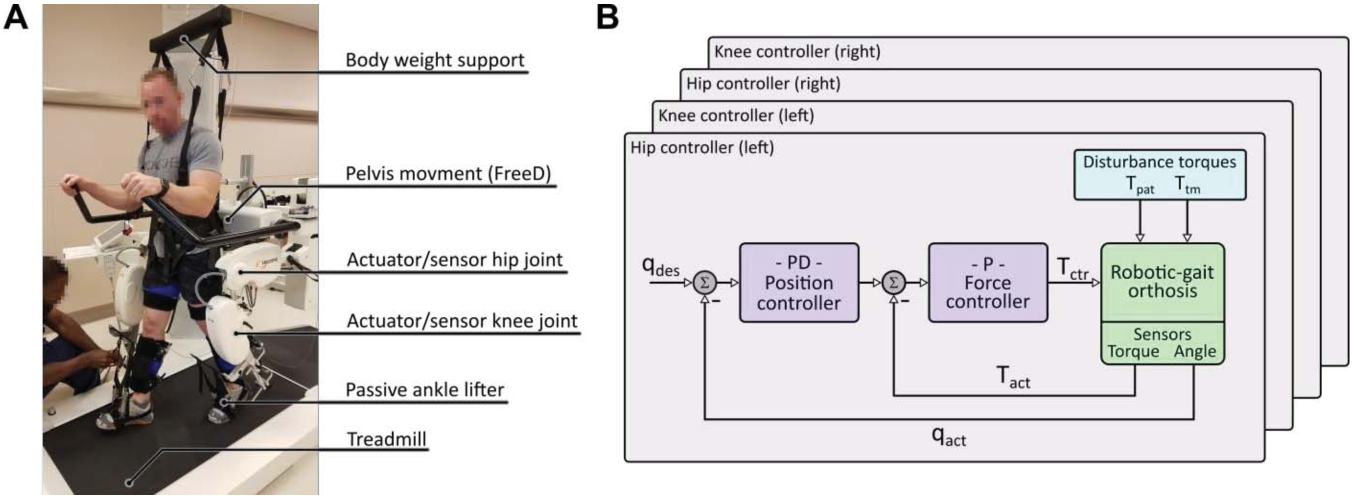

Figure 1: (A) Components of the robot-assisted gait exoskeleton, Lokomat Pro with FreeD V6.2. (B) Cascaded control structure. Primary angle controller based on desired (q_{des}) and measured actual (q_{act}) angles; secondary torque control loop based generates the actuating torque (T_{ctr}) of the exoskeleton; actual torque (T_{act}) measured at the actuators. The disturbance torques by a participant (T_{pat}) and treadmill (T_{tm}). Modified from Jezernik et al. (2003) [7].

METHODS

Subjects. Nineteen adults (9 female, mean (SD) age of 26.3 (5.1) yrs, height of 175.1 (8.8) cm, weight of 73.8 (12.3) kg) without neurological injuries or gait disorders participated. The Institutional Review Board at the Methodist Rehabilitation Center (Jackson, MS) approved the study, and all subjects provided written informed consent prior to the recording session.

Study procedure. The participants walked in the Lokomat Pro V6.2 (Hocoma Inc.) using the impedance control mode. Before the recording session, a physical therapist aligned the hip and knee joints of the device with those of the subject and adjusted the gait parameters to achieve a natural walking pattern. During the recording, the subject was instructed to match the kinematic gait pattern of the device while eight combinations of different Lokomat settings were applied (SP: 1.5 km/h, 3.0 km/h; BWS: 15%, 50%; GF: 60%, 100%). For all trials, the pelvis module (PT) was set to a lateral translation of ±2 cm.

Data recording. The research module of the Lokomat provided output signals of each hip and knee joint (torque, actual and desired angle), as well as the actual BWS. The signals were digitized at 1 kS/s (NI USB 6225, National Instruments Inc., Austin, TX) and post-processed in Matlab 2016 (MathWorks Inc., Natick, MA).

Outcome measures. We calculated the mean of 10 consecutive stride cycles of the hip and knee torques (T_{Hip}, T_{Knee}) and the difference between the desired and actual angle ($A_{des-act}$) for the stance (ST) and swing (SW) phases. For each measure, the average over the left and right legs was used in subsequent analysis. *Statistical analysis.* Descriptive statistical data are presented as mean and standard deviation (SD), and the statistical differences between groups were calculated with a series of three-way repeated-measures ANOVA using SPSS 24.0 (IBM Inc., Armonk, NY).

RESULTS

Figure 2 shows the torques and cyclograms of a representative subject walking at two speeds. At the higher speed, the variability of the robotic support torque increases, as well as the deviation between the desired and actual joint angles. Note that the torque profiles change between different speeds due to an increase in inertial torques.

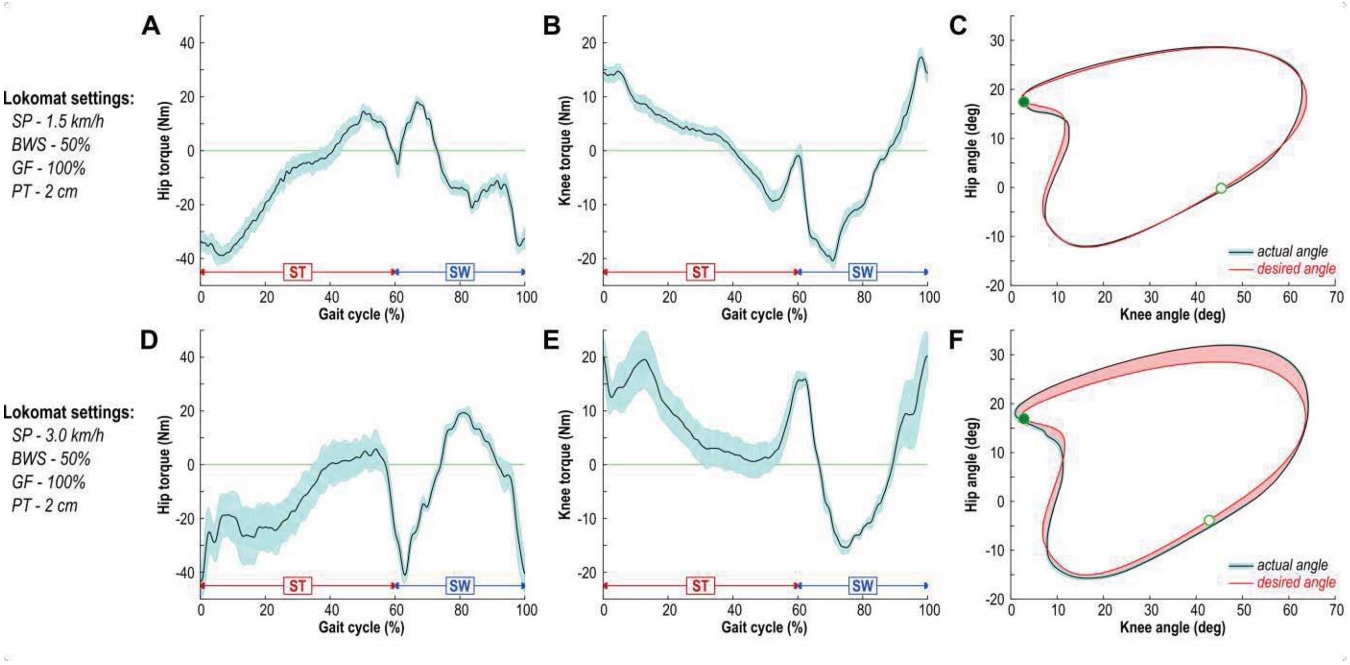

Figure 2: Hip (A, D) and knee (B, E) robotic torques, and hip-knee angle cyclogram (C, F) at 1.5 km/h (top row) and 3.0 km/h (bottom row) treadmill speed of a representative participant (mean and SD of 10 consecutive left gait cycles). In the cyclograms, a full circle (●) marks the beginning of the stance (ST) phase and an open circle (○) the swing (SW) phase.

Tables 1 and 2 present the descriptive statistics and ANOVA results. The following results focus on the main effects of the different Lokomat settings which are presented as the group result (mean, SD) of the relative change due to one factor while the other two factors were collapsed.

Treadmill speed. At higher SP, the deviation between desired and actual angle increases overall by

46.2 (33.3)% for ST and 69.9 (22.8)% for SW. The knee torque increases by 31.7 (46.4)% for ST.

Body weight support. Changing BWS showed the least effect compared to SP and GF. Nevertheless, for a lower BWS, the hip torque increases significantly by 18.8 (32.2)% and 8.1 (14.9)% for ST and SW respectively.

Guidance force. The GF parameter directly modifies the control parameters of the actuated exoskeleton which results in a significant modification of all outcome measures. A decrease in GF from 100% to 60% resulted in a decrease of robotic torque in all joints of 31.9 (23.5)% and an increase in angle deviation of 24.7 (10.0)%.

Table 1: Mean (SD) of the THip, TKnee, and Ades-act during SW and ST over all subjects (n=19).

	SP:	**1.5 km/h**				**3.0 km/h**			
	BWS:	**15%**		**50%**		**15%**		**50%**	
	GF:	**60%**	**100%**	**60%**	**100%**	**60%**	**100%**	**60%**	**100%**
T_{Hip} (Nm)	**ST**	13.67 (5.55)	18.72 (8.86)	12.82 (5.09)	19.37 (6.63)	14.09 (6.49)	32.02 (20.92)	11.79 (4.72)	18.97 (8.75)
	SW	13.58 (4.21)	15.76 (4.08)	14.16 (4.91)	17.01 (4.96)	15.24 (4.06)	20.11 (6.57)	12.47 (6.14)	16.24 (2.97)
T_{Knee} (Nm)	**ST**	5.33 (3.50)	7.43 (4.22)	5.50 (2.74)	7.70 (2.95)	6.88 (3.44)	13.56 (8.96)	7.09 (2.58)	9.43 (4.56)
	SW	10.77 (3.38)	10.70 (2.96)	10.19 (2.86)	10.39 (2.52)	8.26 (3.64)	12.13 (4.74)	8.26 (3.10)	10.65 (2.93)
$A_{des\text{-}act}$ (deg)	**ST**	2.37 (0.94)	1.54 (0.50)	2.19 (0.78)	1.58 (0.33)	3.29 (1.20)	3.43 (1.17)	3.01 (0.94)	2.82 (0.62)
	SW	2.83 (0.81)	1.83 (0.53)	2.63 (0.74)	1.71 (0.49)	5.53 (1.06)	3.93 (0.21)	5.28 (0.95)	3.89 (0.27)

Abbreviations: SP, treadmill speed; BWS, body weight support; GF, guidance force; ST, stance phase; SW, swing phase;

Table 2: Statistical test results on torque and kinematic outcome measures. P-values (partial Eta-squared, $\eta 2$) of the three-way repeated measures ANOVA on the (main and interaction) effects of the factors SP, BWS, and GF.

		SP	BWS	GF	SP * BWS	SP * GF	BWS * GF	SP * BWS * GF
T_{Hip}	**ST**	.176 (.10)	**.021 (.26)**	**.000 (.71)**	**.040 (.21)**	**.042 (.21)**	**.032 (.23)**	**.003 (.39)**
	SW	.286 (.06)	**.025 (.25)**	**.000 (.55)**	**.019 (.27)**	.199 (.09)	.781 (.00)	.307 (.06)
T_{Knee}	**ST**	**.012 (.31)**	.196 (.09)	**.000 (.63)**	.194 (.09)	.140 (.12)	.062 (.18)	**.029 (.24)**
	SW	.192 (.09)	.111 (.14)	**.000 (.57)**	.677 (.01)	**.000 (.52)**	.155 (.11)	.166 (.10)
$A_{des\text{-}act}$	**ST**	**.000 (.64)**	**.027 (.24)**	**.000 (.77)**	.248 (.07)	**.003 (.40)**	.692 (.01)	**.035 (.23)**
	SW	**.000 (.91)**	.100 (.14)	**.000 (.88)**	.868 (.00)	**.042 (.21)**	.329 (.05)	.563 (.02)

Bold = significant ($p < .05$); grey background = large effect size ($\eta^2 > .25$)

DISCUSSION AND CONCLUSION

The results indicate significant changes in the robotic-assistant torques and angle deviations depending on robot settings. In particular, the GF has a pronounced influence on all outcome measures. Since GF directly influences the parameters of the controller, the interaction torques between the participant and the exoskeleton are strongly affected. The Lokomat supports the joint movements according to an ideal trajectory, therefore, at reduced control stiffness, the angle deviations increase while robotic torques decrease. To get robotic torques to zero, a participant needs to exactly match the desired trajectory, overcoming their inertia and that of the exoskeleton, i.e., lower robotic torques indicate higher compliance of the subject towards the desired gait pattern. The higher treadmill speed affects the angle deviations most, which may indicate participants' difficulty in matching the desired gait pattern, especially during the SW phase. In able-body gait, changes in BWS had only minor effects since the subjects can adapt to the changed body weight.

Conclusion. The study demonstrates that robotic torques and angle cyclograms can be informative for evaluating a patient's progress during gait training. Additionally, we raise the awareness for and establish the impact of different Lokomat parameters on gait kinematics and robotic torques, which can enrich the knowledge of rehabilitation progression when used as an assessment tool in research and clinical settings.

ACKNOWLEDGMENTS AND DISCLOSURES

This work was supported by the Yerger Family Fund for NeuroRobotics Research and the Wilson Research Foundation, Jackson, MS. **Financial Disclosures:** The authors have no financial disclosures. **Conflicts of Interest:** The authors have no conflict of interest to declare. **Institutional Review Board Information:** Number: MRC#2017-01, Methodist Rehabilitation Center, 1350 East Woodrow Wilson Drive, Jackson, MS 39216, USA

REFERENCES

[1] K. Y. Nam, H. J. Kim, B. S. Kwon, J.-W. Park, H. J. Lee, and A. Yoo, "Robot-assisted gait training (Lokomat) improves walking function and activity in people with spinal cord injury: a systematic review.," *J. Neuroeng. Rehabil.*, vol. 14, no. 1, p. 24, Mar. 2017.

[2] V. Dietz, G. Colombo, L. Jensen, and L. Baumgartner, "Locomotor capacity of spinal cord in paraplegic patients," *Ann. Neurol.*, vol. 37, no. 5, pp. 574–582, May 1995.

[3] J. Hidler *et al.*, "Multicenter randomized clinical trial evaluating the effectiveness of the Lokomat in subacute stroke.," *Neurorehabil. Neural Repair*, vol. 23, no. 1, pp. 5–13, Jan. 2009.

[4] L. Marchal-Crespo and R. Riener, "Robot-assisted gait training," in *Rehabilitation Robotics*, R. Colombo and V. Sanguineti, Eds. Elsevier, 2018, pp. 227–240.

[5] R. Riener, "Technology of the Robotic Gait Orthosis Lokomat," in *Neurorehabilitation Technology*, D. Reinkensmeyer and V. Dietz, Eds. Cham: Springer International Publishing, 2016, pp. 395–407.

[6] R. Riener, L. Lunenburger, S. Jezernik, M. Anderschitz, G. Colombo, and V. Dietz, "Patient-Cooperative strategies for robot-aided treadmill training: first experimental results," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 13, no. 3, pp. 380–394, 2005.

[7] S. Jezernik, G. Colombo, T. Keller, H. Frueh, and M. Morari, "Robotic orthosis lokomat: a rehabilitation and research tool.," *Neuromodulation*, vol. 6, no. 2, pp. 108–15, Apr. 2003.