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Modeling the Walking Patterns of Reciprocating Gait Orthosis Users with a Novel Lower Limb Paralysis Simulator

W. B. Johnson, S. Fatone and S. A. Gard

Abstract—**A mechanical Lower Limb Paralysis Simulator (LLPS) was developed for able-bodied persons to model the gait of Reciprocating Gait Orthosis (RGO) users. The purpose of this study was to determine if able-bodied subjects ambulating with the LLPS exhibited gait characteristics typical of RGO users. Five able-bodied persons were trained to ambulate with the LLPS and underwent a motion gait analysis. LLPS users were found to exhibit gait patterns that were characteristic of RGO-assisted gait.**

I. Introduction

THE Reciprocating Gait Orthosis (RGO) [1] is a Hip-Knee-Ankle-Foot Orthosis (HKAFO) that enables persons with lower limb paralysis to stand and ambulate upright with the use of crutches or a walker. RGOs are distinguished from other HKAFOs by a reciprocal link that couples the motion of the hip joints so that when one hip extends the other flexes and vice versa. The reciprocal link is intended to promote a reciprocal gait in which each leg is advanced individually, as opposed to a swing-through gait where both legs are advanced simultaneously. Reciprocal gait has a cosmetic advantage over swing-through gait because it better resembles able-bodied gait.

RGOs are often prescribed so that persons with lower limb paralysis may enjoy the physiological benefits of upright ambulation, such as lower incidence of bone fractures and pressure sores [2]. However, ambulating with a RGO is difficult because it is slow and exhausting [3], [4]. Studies have reported that the difficulty of ambulating with RGOs is a contributing factor to their limited use and high rates of abandonment [5], [6]. Increasing the walking efficiency of RGO-assisted gait may allow persons with lower limb paralysis to ambulate with RGOs more frequently and take better advantage of the benefits of upright ambulation.

Unfortunately, investigating RGO-assisted gait is complicated by the difficulty of recruiting RGO users for research. The population of RGO users is small and diverse [7], which makes recruiting a sizable, homogenous sample population challenging as implied by the small sample sizes of RGO studies [7]-[9]. A model of RGO-assisted gait would enable researchers to initially assess hypotheses so that researchers can better allocate the time and resources needed to recruit RGO users to investigations of viable hypotheses.

Mathematical models of RGO-assisted gait have been developed to help predict how changes in RGO design will affect gait dynamics [8]. These models require that assumptions be made about the kinematics or kinetics of gait; however, if modifying RGO design is expected to change both gait kinematics and kinetics, then making informed assumptions to drive the simulation becomes fraught with difficulty. The controlling mechanisms of RGO-assisted gait are currently poorly understood. Therefore, mathematically predicting how gait will change in response to changes in RGO design would require many assumptions, which increases the likelihood of introducing error into the model.

The controlling mechanisms of RGO-assisted gait may not have to be explicitly known to create a useful model. If a system that is analogous to RGO users could be identified, then the behavior of that system could be used to predict that of RGO users. This approach is similar to using animal models in medical research. Able-bodied persons are anatomically and physiologically similar to RGO users except that they lack paralyzed lower limbs and the training necessary to ambulate with those limbs using a RGO. If able-bodied persons were provided with a set of legs that they could not directly move or sense and were trained to ambulate with those legs using a RGO, then they may serve as useful models of RGO users.

A mechanical Lower Limb Paralysis Simulator (LLPS) was designed to provide able-bodied persons with a set of paralyzed legs (Fig. 1). The LLPS is a passive mechanical device consisting of two vertical aluminum tubes connected to a horizontal axle. The vertical tubes serve as the legs of the device. Since RGOs immobilize the knee and ankle joints, the legs of the LLPS have no knee or ankle joints. The distal ends of the legs are attached to Shape&Roll prosthetic feet [10] by pyramid adaptors. The proximal ends of the legs are attached to the horizontal axle by custom clamps. The

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clamps allow the legs to rotate about the long axis of the axle but restrict motion about the orthogonal axes, much like the hip joints of a RGO. Bearings composed of Delrin bushings surrounded by an aluminum cylinder lie between the clamps and horizontal axle to reduce friction. A push-pull cable from an Advanced RGO [11] serves as the reciprocal link between the two axle/hip joints of the LLPS. A crossover clamp attaches a unicycle seat to the middle of the horizontal axle for able-bodied persons to sit on. The unicycle seat elevates the LLPS users so that their anatomical legs hang free above the ground. However, the user's anatomical legs are not attached to the LLPS's legs, preventing them from actuating or sensing the LLPS's legs with their own. LLPS users are secured to the LLPS with a Lumbo-Sacral Orthosis (LSO) that has lateral aluminum bars extending toward the ground. These bars are clamped to another set of bars extending upward from the horizontal axle. LLPS users propel and balance themselves with crutches; much like RGO users would use crutches or a walker for ambulation.

The purpose of this study was to determine if able-bodied LLPS users exhibit some of the distinguishing patterns of RGO-assisted gait. RGO users exhibit some unique gait characteristics that can serve as standards to help determine whether able-bodied persons using the LLPS are reasonable models of RGO users during ambulation. One of these characteristics is that RGO users walk with their trunks flexed forward throughout the gait cycle. Their trunk motion varies sinusoidally about a flexed position, moving closer to the vertical during periods of double leg support and flexing farther forward during periods of single leg support [7]. Another characteristic is that the hip motion of RGO users remains relatively constant during periods of double leg support, but then rapidly changes during periods single leg support [7]. As a result, graphs of their hip flexion angle resemble a square wave. Also, RGO users tend to extend the hip at the beginning of leg swing, which initially moves their leg backward before it swings forward [7]. RGO users also apply vertical forces through their crutches that exceed half of their body weight during periods of single leg support [7]. If LLPS users are to be used as models of RGO users, then they should exhibit these gait characteristics.

II. Methods

A group of able-bodied persons were recruited to train with the LLPS and undergo motion analysis. Written informed consent was obtained from each subject in accordance with the policies of the Northwestern University Institutional Review Board. Subjects learned to ambulate with the LLPS over the course of at least nine thirty-minute training sessions. The subjects initially trained within parallel bars for about a week, and then progressed to using crutches. Training was considered complete when the subject could maintain an average walking speed of at least 0.2 m/s—typical for RGO users [3], [4]—over 60 m to insure that they possessed the stamina needed to complete the data collection session.

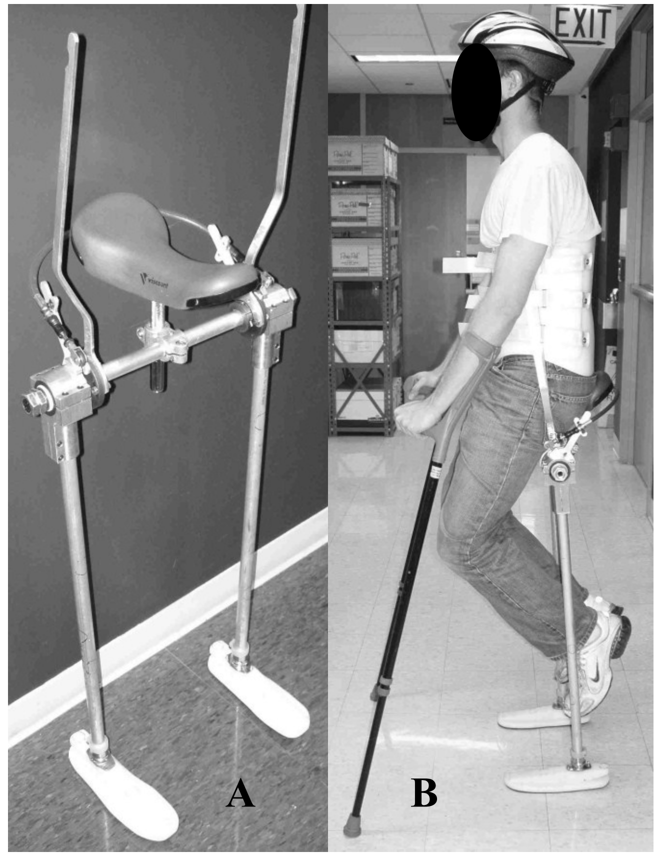

Fig. 1. *A*. Photograph of the LLPS. *B*. Photograph of the LLPS with an able-bodied person.

Data were collected during a single session as the subjects walked back and forth over a level 10 m walkway. A motion capture system (Real-Time, Motion Analysis Corporation, Santa Rosa, CA) tracked the positions of passive reflective markers attached to the subjects, their crutches, and the LLPS at a sampling frequency of 120 Hz. The markers were used to define the position and orientation of the subjects' trunk, upper arms, lower arms, and crutches, as well as those of the LLPS' legs and horizontal axle. Force plates (Advanced Mechanical Technology, Inc., Watertown, MA) embedded flush within the floor measured the ground reaction forces (GRFs) acting on the subjects' crutches. Subjects walked back and forth until data from five crutch strikes were recorded for each crutch when the crutch landed entirely on a single force plate.

Orthotrak software (Motion Analysis Corporation, Santa Rosa, CA) was used to calculate the trunk flexion and hip flexion angles of LLPS users that corresponded to each recorded crutch strike. The trunk flexion angle, hip flexion angle, and vertical GRFs were all normalized to the gait cycle and ensemble averaged over the number of crutch strikes using MatLab software (The MathWorks Inc., Natick, MA). Ninety-five percent confidence intervals (CI) were constructed from trunk flexion, hip flexion, and crutch GRF data collected from five RGO users during a previous experiment using a similar protocol [7]. The averaged data of the LLPS users were then compared to these CIs.

III. Results

Seven subjects gave their informed consent to participate in this study; however, subjects 4 and 5 withdrew from the study after changes to their work schedule prevented them from regularly attending training sessions. Fig. 2A presents the average trunk flexion angles of the five LLPS users who completed training, as well as the 95% confidence interval constructed from the trunk flexion data of RGO users. The data are plotted over the course of a gait cycle, beginning when a foot initially contacts the ground and ending with the subsequent ipsilateral foot contact. Like RGO users, the LLPS users walked with their trunks flexed forward throughout the gait cycle, and their trunk flexion varied sinusoidally with each step. All but one of the LLPS users' data fell entirely within the CI.

Fig. 2B illustrates the average hip flexion angles of the LLPS users and the 95% CI for the RGO users' hip flexion data. The hip flexion curves of the LLPS users resemble square waves: the hip angle remains relatively constant during double leg support, and rapidly changes during single leg support. LLPS users also extend their hips prior to swing, which is illustrated in Fig. 2B by the minima in the hip flexion curves between 60 and 80% of the gait cycle. RGO users exhibit these same movement patterns. The LLPS data lies almost completely within the RGO user CI.

Fig. 2C depicts the sum of the mean vertical GRFs acting on both crutches of the LLPS users during swing phase. Like RGO users, LLPS users exerted forces greater than 40% of their body weight through their crutches during swing phase. Most of the LLPS data lies within the RGO users' CI. However, subject 6 experienced a larger peak force that went beyond that of the CI.

IV. Discussion

This study demonstrated that the LLPS can model characteristic features of RGO-assisted gait. The kinematics and kinetics of LLPS users' gait lie within the variability observed among RGO users, but there were some instances where an LLPS user's data exceeded the bounds of the CI. One of the more notable instances is the trunk flexion for subject 7, which is closer to the vertical than the other LLPS users. Subject 7 was very tall and lean, and the only available LSO that could be used to secure him to the LLPS spanned only his lumbar spine. The LSOs of the other subjects spanned their lumbar spine as well as parts of their thoracic spine; therefore, subject 7's LSO allowed more spinal motion than those used with the other subjects. This additional motion enabled subject 7 to extend his trunk to a greater extent than the other LLPS users.

Another notable deviation from the RGO users' CI was the large vertical GRF acting on subject 6's crutches. These large forces may be the consequence of a particular gait pattern adopted by subject 6. Although all of the subjects were instructed to advance their crutches individually in an

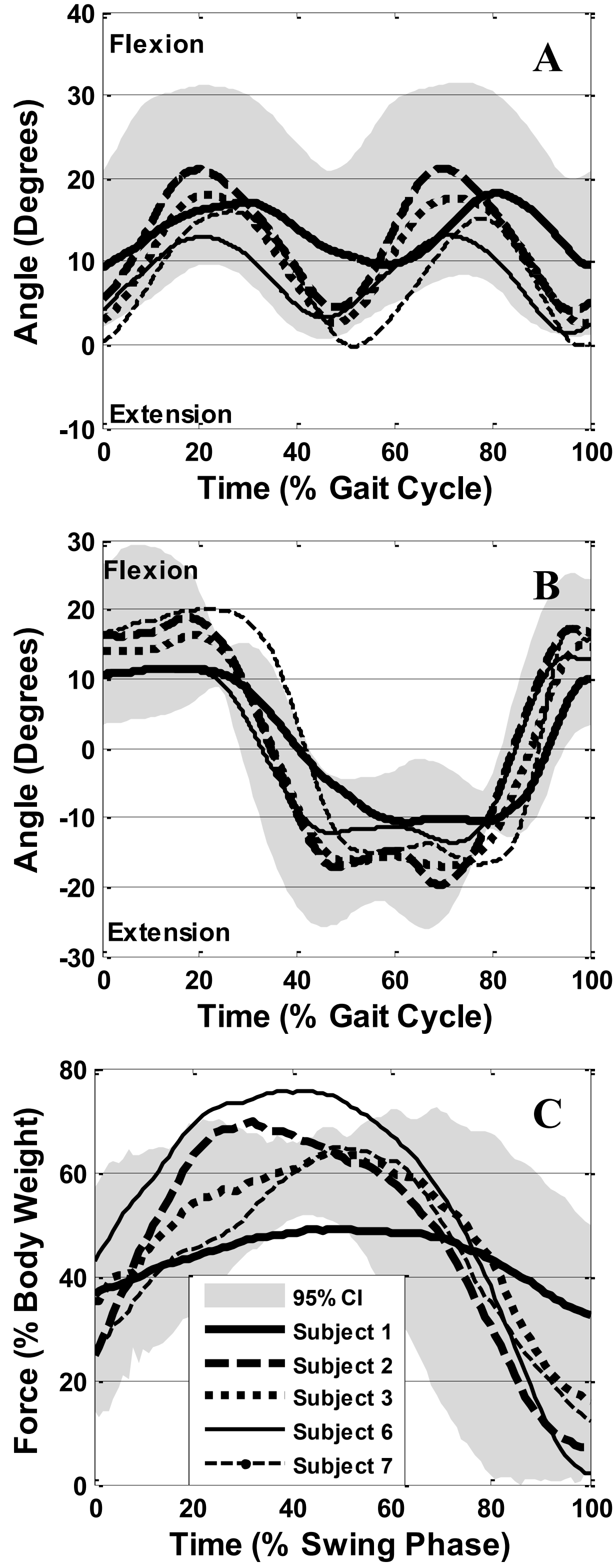

Fig. 2. Comparison of several gait variables between LLPS users and RGO users. Lines represent the mean data for LLPS users and the shaded region indicates a 95% CI calculated from RGO user data. *A.* Trunk Flexion Angle. *B* Hip Flexion Angle. *C* Sum of the vertical GRFs acting on the crutches.

alternating pattern, subject 6 preferred to advance both of her crutches together, which also occurs in swing-through gait.

During swing-through gait, the arms are used to lift both feet completely off the ground during the swing phase, and large forces acting through the crutches are required to accomplish this [12].

Subject 6's gait pattern has also been observed in some RGO users [7]. This combination of reciprocal gait and swing-through gait has been casually referred to as skip-through gait. The fact that subject 6 independently adopted a different gait pattern that also has been observed in RGO users demonstrates the LLPS' ability to robustly model various aspects of RGO-assisted gait, supporting the idea that the LLPS creates sufficient constraints on able-bodied individuals so that they naturally ambulate like RGO users.

Limitations with the LLPS' current design prevent it from precisely modeling all aspects of RGO-assisted gait. For example, the LLPS is unable to simulate varying degrees of paralysis. It most closely replicates conditions created by a complete spinal lesion at L1, and it can not replicate effects that are unique to incomplete lesions or lesions at different levels. However, the gait patterns investigated in this study are common to RGO users with various lesion levels, so the LLPS appears capable of modeling RGO users in general.

Another limitation of the LLPS is that it does not accurately duplicate all of the mechanical properties of RGO users, such as the mass and moment of inertia of the legs, and probably can not be modified to do so effectively. While the mass of the LLPS' legs could be changed to better match those of RGO users, doing so would increase the overall mass of the subject-LLPS system beyond that which the subjects would experience if they actually were paralyzed and ambulating with a RGO. However, the speed of RGO-assisted gait is so slow that the inertial effects of the body segments contribute relatively little to the overall gait dynamics. Therefore, the differences in segment masses and moments of inertia likely do not have an appreciable effect on the output of the model.

Despite its limitations, the LLPS is able to qualitatively model characteristic features of RGO-assisted gait. In this capacity, it can help guide the initial testing and development of hypotheses regarding RGO-assisted gait. The LLPS enables researchers to forego the difficulties of recruiting RGO users in the early stages of hypothesis development, which can facilitate the exploration of RGO-assisted gait. After promising hypotheses have been identified and developed with the LLPS, it can be used to design and streamline the protocol for testing these hypotheses with RGO users. In this way, the LLPS has the potential to be a valuable tool for investigating RGO-assisted gait.

V. Future Work

While this study demonstrates that able-bodied persons walking with the LLPS adopt similar gait patterns to RGO users, it does not definitively indicate that the two gaits are equivalent. Neither does the study validate the assumption that LLPS users employ the same control strategies as RGO users. However, it has provided a foundation for further comparisons between the two systems. More work is needed to identify which aspects of the two systems are analogous, which ones are not, and the relevance of any differences on the efficacy of the model. Furthermore, the true utility of any model lies in its ability to predict previously unknown behavior of the actual system. To test the LLPS' predictive capabilities, new hypotheses regarding RGO-assisted gait need to be evaluated with the LLPS. Then, when viable hypotheses are later evaluated with RGO users, the outcomes can be compared to those collected with the LLPS to determine how well the LLPS predicts the behavior of RGO users.

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