Design of a minimally constraining, passively supported gait training exoskeleton: ALEX II

Article *in* IEEE International Conference on Rehabilitation Robotics : [proceedings] · June 2011

DOI: 10.1109/ICORR.2011.5975499 · Source: PubMed

3 authors:

Kyle Winfree
Northern Arizona University

Paul Stegall
Columbia University

Sunil K. Agrawal
Columbia University

2011 IEEE International Conference on Rehabilitation Robotics
Rehab Week Zurich, ETH Zurich Science City, Switzerland, June 29 - July 1, 2011

Design of a Minimally Constraining, Passively Supported Gait Training Exoskeleton: ALEX II

Kyle N. Winfree, Paul Stegall, Sunil K. Agrawal

University of Delaware
Newark, DE 19716
{winfree,stegall,agrawal}@udel.edu

***Abstract*— This paper discusses the design of a new, minimally constraining, passively supported gait training exoskeleton known as ALEX II. This device builds on the success and extends the features of the ALEX I device developed at the University of Delaware. Both ALEX (Active Leg EXoskeleton) devices have been designed to supply a controllable torque to a subject's hip and knee joint. The current control strategy makes use of an assist-as-needed algorithm. Following a brief review of previous work motivating this redesign, we discuss the key mechanical features of the new ALEX device. A short investigation was conducted to evaluate the effectiveness of the control strategy and impact of the exoskeleton on the gait of six healthy subjects. This paper concludes with a comparison between the subjects' gait both in and out of the exoskeleton.**

I. Introduction

One major drawback facing exoskeletons today is the limited freedom the user feels while wearing the device. If the weight of the device is supported by a platform, it generally decreases the degrees-of-freedom allowed by the user. While this may be suitable when using the device for the rehabilitation of individuals with severely impaired motion, such as spinal cord injury patients, it may limit the comfort and quality of rehabilitation for less impaired individuals. Another solution is to design a free standing device; these are devices that are either supported by the users [5], [8] or through control strategies such as zero moment point support [9]. User supported devices however, require some level of control from the user, which may not be available in impaired individuals. Freestanding devices supported using active controls limit device orientation and configuration to maintain balance. While these orientations are similar to those required by the user to maintain balance on their own, it may be a limiting factor when trying to rehabilitate gait patterns.

The variety of control strategies currently in use are as diverse as the strategies themselves. Some of the current

Fig. 1: A CAD model of the ALEX II device.

strategies are guided position control, assist-as-needed, and error enhancement haptic disturbance.

Guided position control is used to move the leg through a prescribed motion. This is the simplest of the control strategies, but moves the subject the same way, regardless of the input or intention of the user. Hornby et al [4] noted the Hocoma Lokomat[1], a commercial robotic gait rehabilitation device, uses this kind of guided training algorithm and motions are "limited to the sagittal plane." While the Lokomat may be an effective tool for spinal cord injury patients, its effectiveness for less impaired individuals may not be optimal. Duschau-Wicke et al [3] also suggests that position control may not be the best means of control if training a adequately able and independent subject.

[1]Lokomat®, Hocoma Medial Engineering Inc, Zurich, Switzerland

Assist-as-needed control is also used to help the user follow a prescribed motion, but only if the user sufficiently deviates from the desired trajectory. Banala et al [2] and Kim et al [6] used this method in gait training with the ALEX I device.

Error enhancing controls work similarly to the assist as needed control, except that when the subject deviates too far from the prescribed path, a force is applied to move the leg further from the path. This method requires the subject to be more involved in following the path, but is less widely used in gait training due to the risk of forcing the subject into a gait that wouldn't allow them to walk safely. Lee and Choi [7] demonstrated the efficacy of this control method in 2D upper limb trajectory training.

Other control strategies include the use of other sensors to distill user intention. Yano et al [10] use pressure sensors in the shoe to sense the shift of weight of the subject. This approach is similar to the position control, but instead is user cued.

II. ALEX II

The ALEX II device (Figure 1), designed and manufactured in house at the University of Delaware, is a new active leg exoskeleton device for robotic gait rehabilitation. Like the previous device [2], this version of ALEX is able to apply torques at the hip and knee joints of users. Users include healthy young individuals, healthy elderly individuals, and elderly stroke patients. The leg of the device is supported from the rear by a back support, which also attaches to the human user. The unilateral leg has been designed to be used on the subject's right or left leg. Several adjustments within the exoskeleton leg can also be made, so as to improve fit to the user.

The bulk of the device is made from 6061 Aluminum. ABEC bearings are used in all passive revolute joints. Springs for gravity balancing were custom cut from stock lengths to achieve the desired spring stiffness.

A. Back Support

Neither the weight of the leg or back support are borne by the subject, but instead the back support provides configuration independent gravity compensation for the device. The back support consists of a series of spring compensated links. Links which act against gravity are balanced by springs relocated outside of the support that are able to emulate zero free length springs. This support system allows for four uncoupled degrees-of-freedom; see Figure 2. Two parallel link systems provide the anterior-posterior motion (C) and superior-inferior motion (B). The two parallelogram linkages decouple these two motions and are gravity balanced. It should be noted that (B) has a noticable amount of friction, due to the tension running over the cable routing pulleys. Two more degrees-of-freedom provide side-to-side translation (A) and rotation about a vertical axis (D). Passive gravity balancing was accomplished using the methods previously described by Agrawal et al [1]. In this device the concept has been extended to gravity balance two degrees of freedom simultaneously.

The previous version (ALEX I) has one parallelogram linkage similar to (B), at the end of that linkage there are V-groove rails that provide side to side motion, then there is a revolute joint corresponding to (D). It does not have a degree of freedom in the forward/backward direction, so when its linkage moves up or down the subject moves slightly back. The ALEX I is supported by a vertical spring that is adjustable so that the subject doesn't feel the weight of the exoskeleton when standing normally, when they raise above that point they feel a small portion of the weight, if they are below that point the spring provides an upward force.

B. The Leg

In order to accommodate users having either a left or right paretic leg, the exoskeleton leg can be easily switched between each side. This is achieved with two easy release latches on a revolute joint in the transverse plane (which rotate when the clips are removed during side switching) and a single easy release carabiner that connects a retaining spring to the adduction/abduction joint. ALEX I could only be used on the right side. The length of each leg joint is adjustable so as to accommodate for different sized subjects. Additionally, the distance to each leg segment from the exoskeleton is adjustable. This is provided because subject thigh and shank widths do vary; failure to accommodate for this difference can result in inappropriately aligned joints. There are also several different sized cuffs to allow for different leg thicknesses.

Three adjustable prismatic joints adjust to the subject's pelvic width (E), thigh length (H), and shank length (J), similar to its predesessor. Not shown are the two additional prismatic adjustments that extend from the exoskeleton in the frontal plane to mate the orthotics to the subject's leg. These are located near the thigh and shank length adjustments (H,J).

The support for the hip motor allows for adduction and abduction through a revolute joint behind the subject's femoral head (F). In addition, the hip (G) and knee (I) can flex and extend in the sagittal plane, like the previous design. There is an additional degree-of-freedom allowing rotation about a vertical axis through

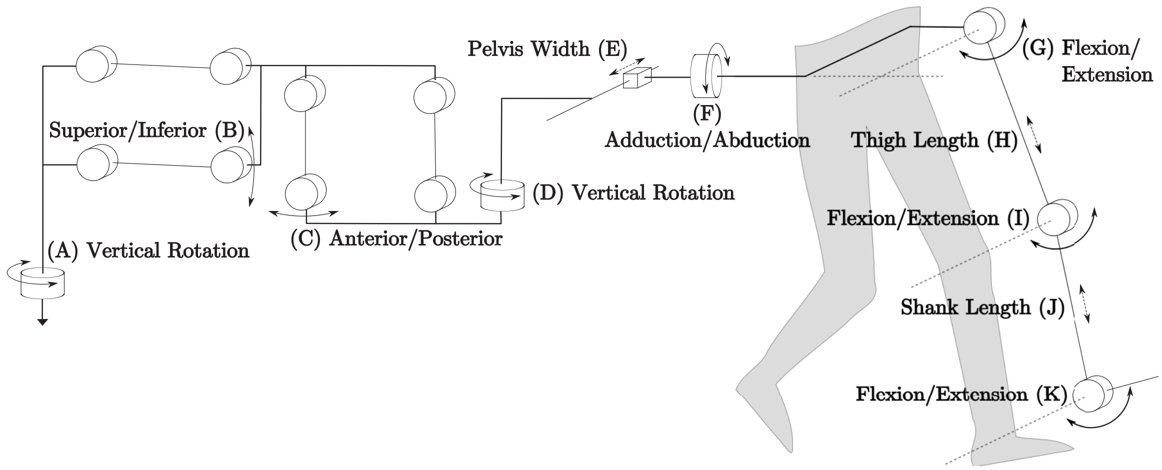


Fig. 2: Shown here is a schematic representation of the ALEX II open chain manipulator.

a parallel linkage system (not shown in Figure 2). This allows for medial and lateral rotations of the leg, with those rotations taking place along the longitudinal axis of the leg. This degree-of-freedom has however been temporarily locked, as the momentum of the linkage when walking caused unwanted leg rotation.

There is an encoder on the ankle used to measure its joint angle (K). This is a completely passive component made of lightweight polypropylene, it is only there to provide the ankle angle and does not apply joint torque. ALEX I has a similar joint which uses a shoe insert that requires the physical therapist to put the subjects shoe on while the subject is in the device; this is rather difficult to do. The current ankle joint can be put on the subject before getting into the exoskeleton.

C. Actuation

In ALEX I, linear actuators were used. These actuators have a limited range of motion, which consequently limited the range of motion of the leg. Actuator control was also dependent on the segment length; if a subject's segment lengths were too long or too short, those subjects could not participate in ALEX I studies because the device is unable to produce the full range of motion characterized by normal gait. ALEX II instead uses two Kollmorgen ACM22C[2] rotary motors, geared by Thomson Micron[3] 1:50 and 1:60 gearboxs at the hip and knee joints respectively. These motors provide the torque commanded by the controller. Transducer Techniques TRS-500 and TRS-1k load cells provide the feedback for a closed loop control of hip and knee torque respectively. The motors provide the workspace of anthropometric exoskeleton leg similar to the human leg.

D. Control

A dSPACE 1103[4] control system is used to implement the real time controls and all data collection. The low level controller has been designed to accommodate for gravity and drive train friction. Please see Figure 3. Control is managed by torque regulation. When walking in the exoskeleton, but without the force field (explained in the next paragraph), the system regulates the torque at each joint to be zero. In this way, when the user applies a torque to the system, they effectively guide the exoskeleton to follow their movements.

During gait training a force field is applied to the leg. The torque control is determined by modeling a virtual spring, similar to that used in [2]. From the virtual spring, a normal force is found. This force, found in the Cartesian coordinate system, guides the subjects leg back to the desired trajectory. This only happens when the deviation from the desired trajectory, as measured by the normal distance, exceeds an adjustable threshold. The properties of that spring can be easily changed by the therapist to suit the needs of the subject. The same properties used in previous studies [6] were used in this study. The threshold distance can also be set by the therapist and is generally widened as the subject learns the new gait pattern. A force tangent to the trajectory can be applied to the leg if the subject is having difficulty maintaining walking speed. This tangent force is only applied when the subject is sufficiently close to the target trajectory. Tangent force is inversely related to the

[2]Danaher Corporation, Washington D.C., USA
[3]Danaher Corporation, Washington D.C., USA
[4]dSPACE GmbH, Paderborn, Germany

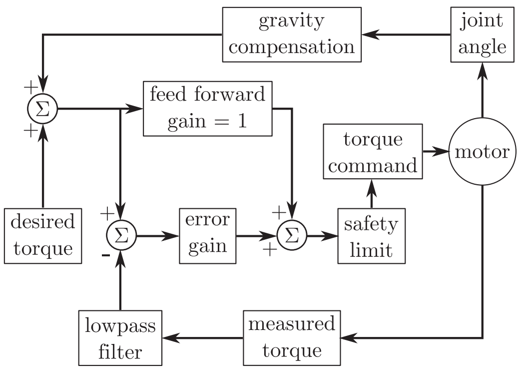


Fig. 3: The low-level controller used in ALEX II. Note this is a torque regulator, where the set point changes according to training or free walking.

TABLE I: Testing protocol.

task	duration (min)
free motion to find preferred speed	5
free motion at reduced speed	5
break	15
verify reduced speed in-exoskeleton	5
break	5
in-exoskeleton with force field disabled	10
break	5
in-exoskeleton with force field enabled	12
Total Time	**62**

distance from the trajectory, as the deviation becomes larger, the force provided is lessened. This encourages proper path following rather than focusing on overall speed.

E. Additional Sensors

Each shoe worn by the subject is instrumented with three Interlink Electronics FSR 406[5] pressure sensors, mounted at the heel, ball, and toe of the foot. These provide information about foot contact with the treadmill. This is used in offline data processing and soon coordination with a functional electrical stimulation unit. They may also be used for robotic leg control in the near future.

Two ATI[6] Mini-45 six degree-of-freedom force-torque (F_x, F_y, F_z, τ_x, τ_y, τ_z) sensors mate the exoskeleton to each orthotic. This is used for offline processing and is expected to soon be extended to use in the real time controller as well.

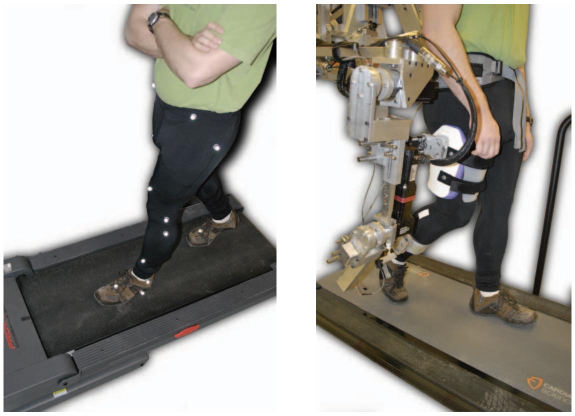
III. Study

Six participants were included in a short investigation to the efficacy of the ALEX II device. These were healthy young college students, chosen as a convenience sample. Potential participants were excluded if they had previous experience with an active gait orthosis. All participants were between 25 and 32 years old without any physical impairments that affect ambulation on a treadmill. No subjects withdrew from this investigation. All subjects read and signed a statement of informed consent and were aware they reserved the right to withdraw at any time without consequence. Subject motion in free motion (not in-exoskeleton) was captured by a Vicon Bonita[7] system. Motions in-exoskeleton were recorded by the device itself.

Subjects first walked on a treadmill to find their preferred walking speed. The speed was then reduced to 82%; this reduction value was found empirically in previous work by the authors comparing the free motion preferred speed to the in-exoskeleton preferred speed (this study will be expanded on in the next paragraph). The subjects then walked at this speed while their motion was again captured. After a break, they were fitted to and walked in the ALEX II exoskeleton device. The first five minutes was to verify that the walking speed was comfortable and to adjust to walking in an active leg exoskeleton. They were given another break, after which they walked for ten more minutes, the gait cycles from this period were averaged to form the baseline trajectory. This was followed by another break and walking in ALEX II for twelve minutes trying to follow a target trajectory using the force field and visual feedback. The target trajectory was their baseline trajectory but with the hip and knee angles reduced by 20%. This reduction at both joints was chosen to be challenging while avoiding problems with foot scuffing, increasing the joint excursion would have avoided all foot scuffing potential but would introduce the possibility of going outside of the subjects safe range of motion.

In the prior study to determine the preferred walking speed in the device subjects first walked freely on a treadmill, while blinded to the speed display, to determine their preferred walking speed to the nearest tenth of a mile per hour. They were then fitted to the exoskeleton and repeated the same process. The average reduction in preferred walking speed among the subjects was 82%.

[5]Interlink Electronics, Camarillo, CA, USA
[6]ATI Industrial Automation, Apex, NC, USA
[7]Vicon Motion Systems, Oxford, UK



(a) Camera motion capture. (b) In-exoskeleton data capture.

Fig. 4: Data acquisition during both free motion and in-exoskeleton walking.

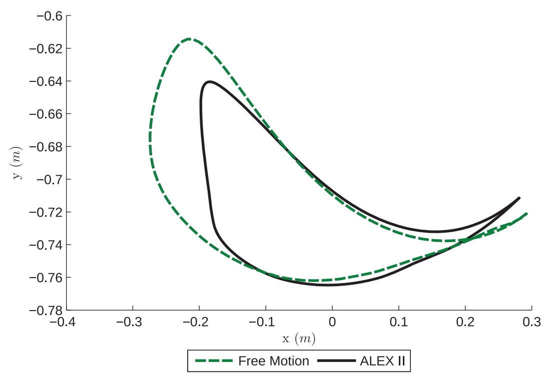


Fig. 5: This figure shows a comparison of the position of left lateral malleolus, relative to left greater trochanter, of both free motion and in-exoskeleton motion. Here positive x reflects the location of the maleolus anteriorly of the coronal plane; negative x is then placement posterior of the coronal plane. Negative y reflects the vertical drop inferior of the femoral-accetabular joint.

IV. Results and Discussion

Figure 5 shows a representative comparison of the path of the malleolus, relative to the greater trochanter, while walking with and without the exoskeleton. The greater trochanter is used as an approximation of the location of the femoral accetabular joint in the sagittal plane. From this figure, one can see some differences between free motion and in-exoskeleton motion. First, it is clear that the leg doesn't go as far back. Second, there is a compression of the trajectory along the *x-axis* at toe off. One possible explanation is that the subject is reacting to the inertia of the exoskelton and

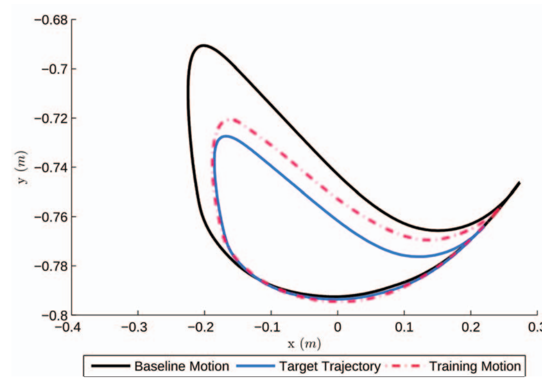


Fig. 6: Position of left lateral malleolus, relative to left greater trochanter, in sagittal plane. These trajectories were generated from forward kinematics of the human joint angles as measured by the ALEX 2 device. Note the difference between the baseline and target trajectory. Despite this large difference, the subject followed the a trajectory close to the target than their baseline when the force field was enabled. The coordinate frame is the same as in Figure 5.

not rolling as far onto the ball of their foot. As such, they may pick up their foot earlier in the gait cycle. It also seems reasonable that this could be caused by backlash in the orthotics when they are changing direction. By measuring motion with the exoskeleton, instead of with the motion capture system, there is no way to tell conclusively which is the cause. A future study that also captures motion with the camera system when using the exoskeleton may reveal such backlash. The reflective nature of the exoskeleton and the size of the linkages may interfere with the cameras' view of the markers, complicating a reliable assessment using a camera system.

Figure 6 shows a representative sample of the baseline trajectory, a modified target trajectory, and the path traced when the force field is enabled for one user. It can be seen that the subject is following closer to the target trajectory when the force field is on than the baseline alone (force field off). This demonstrates that the assist as needed controller is providing feedback to the subject. Further work is expected to extend this training, and possibly explore different control strategies.

V. Conclusion

ALEX has been redesigned to provide less encumbered motion to its users and to improve the quality of training provided to subjects. While a preliminary study does show that ALEX II has potential for use in gait training, there are some differences between gait in ALEX II and natural gait. A future study needs to be done to determine the source of these differences and evaluate their impact on learning in rehabilitation. Without more extensive testing it cannot be determined if ALEX II gives better training results than ALEX I, but it can accommodate a wider variety of subjects, is easier to use, and can provide a wider range of motion.

ACKNOWLEDGEMENTS

The authors would like to thank the machinists who helped with design and fabrication, Steve Beard, Dave Cowgill, and Al Lance. We would also like to thank the study participants.

REFERENCES

[1] A. Agrawal and S. K. Agrawal. Design of gravity balancing leg orthosis using non-zero free length springs. *Mechanism and Machine Theory*, 40(6):693–709, 2005.

[2] S. K. Banala, S. H. Kim, S. K. Agrawal, and J. P. Scholz. Robot Assisted Gait Training With Active. *IEEE transactions on neural systems and rehabilitation engineering : a publication of the IEEE Engineering in Medicine and Biology Society*, 17(1):2–8, 2009.

[3] A. Duschau-Wicke, A. Caprez, and R. Riener. Patient-cooperative control increases active participation of individuals with SCI during robot-aided gait training. *Journal of neuroengineering and rehabilitation*, 7:43, Jan. 2010.

[4] T. G. Hornby, D. D. Campbell, J. H. Kahn, T. Demott, J. L. Moore, and H. R. Roth. Enhanced gait-related improvements after therapist- versus robotic-assisted locomotor training in subjects with chronic stroke: a randomized controlled study. *Stroke; a journal of cerebral circulation*, 39(6):1786–92, June 2008.

[5] H. Kazerooni, J.-L. Racine, L. Huang, and R. Steger. On the control of the berkeley lower extremity exoskeleton (bleex). In *Robotics and Automation, 2005. ICRA 2005. Proceedings of the 2005 IEEE International Conference on*, pages 4353 – 4360, 2005.

[6] S. H. Kim, S. K. Banala, E. a. Brackbill, S. K. Agrawal, V. Krishnamoorthy, and J. P. Scholz. Robot-assisted modifications of gait in healthy individuals. *Experimental brain research. Experimentelle Hirnforschung. Experimentation cerebrale*, 2010.

[7] J. Lee. Effects of Haptic Guidance and Disturbance on Motor Learning : Potential Advantage of Haptic Disturbance. *Structure*, pages 335–342, 2010.

[8] S. Lee and Y. Sankai. Power assist control for walking aid with hal-3 based on emg and impedance adjustment around knee joint. In *Intelligent Robots and Systems, 2002. IEEE/RSJ International Conference on*, 2002.

[9] K. Low, X. Liu, and H. Yu. Development of ntu wearable exoskeleton system for assistive technologies. In *Mechatronics and Automation, 2005 IEEE International Conference*, 2005.

[10] H. Yano. Gait Rehabilitation System for Stair Climbing and Descending. *Symposium A Quarterly Journal In Modern Foreign Literatures*, pages 393–400, 2010.