Assisting paretic ankle motion with a soft exosuit can reduce whole-body compensatory gait patterns and improve walking efficiency for patients after stroke

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Summary

Conventional neurorehabilitation approaches after stroke have had limited success at restoring walking function, often resulting in compensatory gait patterns that lead to energetically inefficient walking. In this paper, we present a soft exosuit to assist walking that can benefit poststroke gait rehabilitation. The exosuit combines textile garments with cable-driven actuators and is lighter and more compliant compared to traditional rigid exoskeletons (Asbeck et al., 2015). The exosuit for a poststroke population provides unilateral assistance to the paretic ankle motions. In a feasibility study with nine chronic poststroke patients on the treadmill, we found that the exosuit can change paretic ankle kinematics in sagittal plane, while minimal changes were observed from kinematics of other joints in sagittal plane. Furthermore, the ankle assistance resulted in reduced compensatory gait patterns and ultimately reduced metabolic cost of walking. These preliminary results demonstrate the feasibility of exosuits for poststroke gait assistance and potentially poststroke gait training.

Introduction

Stroke is a leading cause of long-term disability, with over 33 million stroke survivors worldwide. Over 80% of stroke survivors live with residual gait impairments despite extensive therapy (Mozaffarian et al., 2016). The impairments often result in the development of compensatory patterns with a slow and energetically inefficient gait, contributing to a reduced physical activity and quality of life after stroke.

To address the limitation of current rehabilitation strategies after stroke, researchers have been investigating how robotic technologies can be applied to gait rehabilitation. In particular, rigid exoskeletons have been widely investigated for rehabilitative use, and showed promising outcomes when applied to patients with severe loss of gait function (Chen et al., 2013). Yet, there have not been many studies which showed that robotic technologies could make significant positive outcomes from poststroke patients with partial mobility.

In this paper, we present our preliminary results from human subject testing which demonstrate that a soft exosuit can improve mechanics and energetics of poststroke walking.

Methods

Ankle impairment is prevalent after stroke and is often characterized by foot drop and significant gait asymmetry. In particular, foot drop is a primary contributor to compensatory gait patterns such as hip hiking and circumduction. We hypothesized that restoring paretic ankle function would result in changes to whole-body gait mechanics and ultimately produce more natural and efficient walking. To restore paretic ankle function, we developed a stroke-specific unilateral exosuit (Fig.1a) that can assist paretic ankle motions in the sagittal plane—i.e. ankle dorsiflexion (DF) and plantarflexion (PF)—through a biologically-inspired flexible textile structure (Bae et al., 2015).

To test this hypothesis, we conducted a feasibility study with nine chronic poststroke patients (Age: 51±6 years, weight: 80±8 kg, walking speed: 0.93±0.18m/s, years after stroke: 3±1 years) using this stroke-specific exosuit and a tethered lab-based exosuit actuation testing platform that transmits mechanical power from off-board actuators through bowden cables (Fig. 1b). Two 8-minute treadmill walking bouts were compared: one wearing inactive suit (unpowered) and one wearing active suit (powered). Multiple data were collected during the testing using various sensor

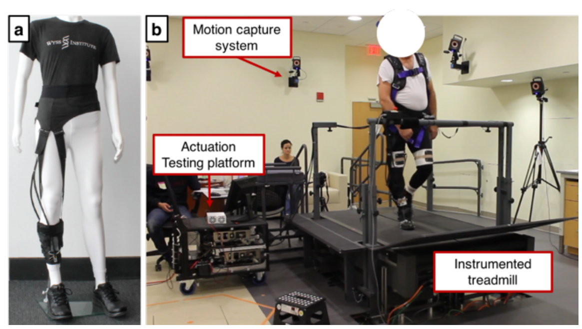

Figure 1. a. Stroke-specific exosuit b. Human subject testing environment

instruments. These included a Cosmed K4b2, 9-camera Vicon motion capture system, Bertec instrumented treadmill, and exosuit-integrated sensors. Several gait parameters were calculated to evaluate exosuit performance: joint kinematics and kinetics, foot COM trajectory, and mass-normalized oxygen consumption per meter ambulated (energy cost of walking). Foot COM trajectory was used to measure gait circumduction, defined as the maximum frontal plane deviation of the foot during swing phase from its average stance phase position.

Results

Significant changes in paretic ankle kinematics in sagittal plane were observed when the suit was powered. Specifically, foot drop, measured as the difference between the paretic ankle angle at initial contact (IC) and Toe off (TO), was reduced (Baseline: -0.99±8.55°, Active: 8.41±5.80°, $p<0.001$), and paretic ankle angle at IC (i.e. ankle landing position) became more neutral (Baseline: -9.43±7.94°, Active: 0.80±5.86°, $p<0.001$) (fig 2.a). Conversely, no statistically significant changes in paretic hip and knee sagittal plane kinematics were observed, nor in any of the joints on the non-paretic limb (fig 2.b).

Furthermore, a significant improvement in participants' metabolic cost of walking was observed with the suit powered versus unpowered (12±2% reduction, $p = 0.02$). To validate our hypothesis that reduced compensatory motions would underlie improved gait efficiency, a sub-group analysis was performed based on patient-specific compensatory gait patterns. Specifically, the patient group who had circumduction reduced their paretic lateral foot trajectory ($N = 3$, Baseline: 8.49±3.52cm, Active: 5.54±2.70cm, $p=0.03$) (fig 2.c).

Discussion

The experimental results validated our hypothesis that the unilateral assistance to the paretic ankle from exosuit leads to changes in whole-body walking mechanics and a reduced cost of transport for patients after stroke. All patients showed positive change in their paretic ankle kinematics in sagittal plane, patients with compensatory patterns changed their whole-body gait pattern, and finally metabolic cost of walking was significantly reduced when comparing the suit unpowered to powered. The reductions found in energy cost are in line with what was found in healthy individuals during loaded walking with similar levels of assistance on both legs [Ding et al., 2016]. The fact that compensatory pattern and metabolic energy cost walking reduced at the same time, while no significant change was observed from sagittal plane kinematics of other joints suggests that the reduction of energy cost

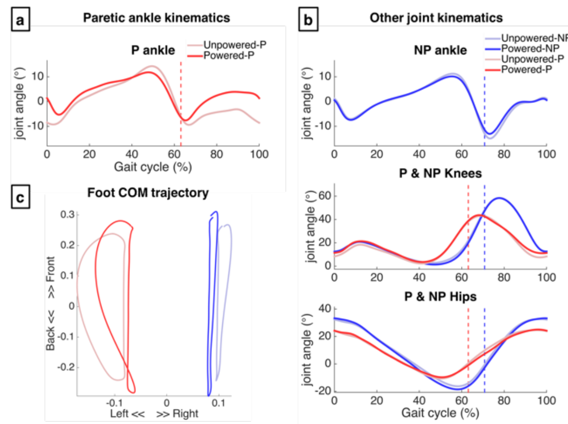

Figure 2. a. Paretic ankle kinematics averaged over nine patients. b. Kinematics of other joints averaged over nine patients. P: Paretic, NP: Non-paretic. The dotted vertical lines in a. and b. indicate when swing phase starts. c. The change of Foot COM trajectory from a patient with circumduction.

of walking was mainly caused by the change of paretic ankle motion and reduced compensatory motion.

This abstract presents a demonstration of the feasibility of improving gait mechanics and economy for patients poststroke during treadmill walking using a tethered soft exosuit. Future work will be focused on studying the effects during overground walking.

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References

Mozaffarian D., Emelia JB., Alan SG. et al. (2016), Heart disease and stroke statistics-2016 update: a report from the American Heart Association, Circulation, pp.CIR-0000000000000350. doi: 10.1161/CIR.0000000000000350

Chen G, Chan CK, Guo Z, Yu H (2013), A review of lower extremity assistive robotic exoskeletons in rehabilitation therapy. Critical reviews in biomedical engineering. 2013;41(4-5):343–63. doi: 10.1615/CritRevBiomedEng.2014010453

Bae J, De Rossi SMM, O'Donnell K., Hendron KL., Awad LN., Dos Santos TTR, De Araujo VL., Ding Y., Holt KG, Ellis TD., Walsh CJ. (2015), A soft exosuit for patients with stroke: Feasibility study with a mobile off-board actuation unit. Rehabilitation Robotics (ICORR) IEEE International Conference on, pp. 131-138. doi: 10.1109/ICORR.2015.7281188

Asbeck AT., De Rossi SMM., Holt KG., and Walsh CJ. (2015), A biologically inspired soft exosuit for walking assistance, The International Journal of Robotics Research 0278364914562476. doi:10.1177/0278364914562476

Ding Y., Galiana I., Asbeck AT., De Rossi SMM., Bae J., Santos T., Araujo V., Lee S., Holt K., Walsh C. (2016), Biomechanical and Physiological Evaluation of Multi-joint Assistance with Soft Exosuits, in IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol.PP, no.99, pp.1-1 doi: 10.1109/TNSRE.2016.2523250