Alteration of push-off mechanics during walking with different prototype designs of a soft exoskeleton in people with incomplete spinal cord injury – a case series

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Abstract— **The push-off is a key factor determining the walking capability. People with impaired function due to incomplete spinal cord injury (iSCI) have altered biomechanics and are, therefore, at a disadvantage during activities of daily living such as walking. XoSoft is a prototype soft exoskeleton designed to assist during walking. Different generations of XoSoft followed different strategies of tailoring the garment (custom-made vs. one-size fits all). This may result in altered effects on the mechanics of walking. In this study, we assessed two generations of XoSoft with three people with iSCI and focused on the push-off mechanics (ankle kinematics & kinetics) during level walking. The results showed that XoSoft was able to support the gait, but systematic differences between prototype generations were not found. Consequently, a more general approach for the garment design may be feasible.**

I. Introduction

THE ankle joint and its ability to produce power during push-off is highly relevant for gait [1], [2]. It has been shown that modulation of the peak ankle power has direct impact on the workload of the proximal leg muscles [2]. If people are unable to produce the necessary power at the ankle, due to impairments such as incomplete spinal cord injury (iSCI), the more proximal joint muscles, mainly at the hip, may need to compensate in order to allow for walking ability, which presents a mechanical disadvantage. It has been shown that people with iSCI have altered ankle kinematics and kinetics during different walking tasks [3], [4]. Also, it has been shown that the plantarflexor muscles have diminished ability to produce torque [5]. Consequently, they are at a disadvantage during everyday motion tasks such as walking.

Previous work using custom powered ankle-foot orthoses supporting the plantarflexion have shown that the ankle range of motion was increased with a powered orthosis compared to no orthosis [6] and that the dynamics of the push-off could be improved [7].

In the XoSoft project, prototypes for a modular, soft, exoskeleton have been developed following a user-centered approach [8].The goal is to provide assistance for people with impaired walking due to diagnoses such as iSCI. The aim of this study was to assess the effect of the ankle actuation of XoSoft on the ankle joint and dynamics of walking during the push-off in people with iSCI.

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II. Methods

A. XoSoft

The detailed technical description of XoSoft has previously been published [9]. Participants were tested wearing both the Beta2 and the Gamma prototype. All had plantarflexion actuation, which stores energy using a textile based clutch in series with an elastic band during the stance phase and releases it during terminal stance and initial swing phase (Participant 1 & 3: bilateral, Participant 2: right side). The main difference between Beta2 and Gamma prototype was the garment: Beta2 had tight custom-tailored garments while for Gamma a loose design suitable for various participants was chosen.

B. Participants

Three male participants with iSCI and normal range of motion in the lower extremity joints (Table I) performed gait analysis at two separate time points. In both sessions, they were tested first without XoSoft (None) and then with the prototype (XoSoft).

TABLE I
PARTICIPANT CHARACTERISTICS

	Participant 1	Participant 2	Participant 3
Age [years]	79	71	55
Height [m]	1.57	1.68	1.64
Mass [kg]	55.8	63.4	78.3
Diagnosis	Hereditary spastic paraplegia	Traumatic spinal cord injury	Hereditary spastic paraplegia
Walking impairment	Paraspastic gait with partial toe dragging. Able to walk without aid.	Paraspastic gait combined with spinal ataxia. Uses two trekking poles for community walking.	Paraspastic gait with partial toe dragging. Wears an ankle foot orthosis on left side for community walking.

C. Data collection

Gait kinematics were collected with markers and a 3D optoelectronic camera system (Vicon Vantage, Vicon Motion Systems) and calculation of joint angles followed a standardized approach [10]. Simultaneously, ground reaction forces were collected using in-ground force plates (AMTI

Inc). Kinetic data was calculated using an inverse dynamics approach (Bodybuilder, Vicon Motion Systems). All subsequent analysis was done with Matlab (Matlab Inc.)

Each participant performed four walking trials with each condition at a self-selected speed. The self-selected speed was determined during the None condition and had to remain consistent for the XoSoft condition to ensure comparability of the kinematic and kinetic results.

III. Results

All participants had increased peak ankle plantarflexion angles during push-off with XoSoft (except participant 3, left, Gamma; Table II). The maximal ankle angular joint power showed small increases of XoSoft compared to None for participant 1 and divergent results between prototypes for participants 2 and 3. The anterior ground reaction force impulse showed small changes: increasing impulse for Beta2 compared to None, while Gamma had reduced values compared to None (except participant 2 right ankle).

TABLE II
DIFFERENCE OF DISCRETE VALUES OF ANKLE BIOMECHANICS AND KINETICS: XOSOFT VERSUS NONE (MEAN OF 4 TRIALS)

		Participant 1		Participant 2	Participant 3	
		L	R	R	L	R
Angle [°]	β2-θ	3.1	1.9	5.1	8.4	4.5
	γ-θ	0.5	1.5	9.7	-1.4	0.1
Power [W]	β2-θ	5.6	16.7	-35.3	7.8	0.0
	γ-θ	6.1	18.5	20.5	-24.8	-90.8
GRF Imp. [Ns]	β2-θ	0.8	0.4	0.7	0.7	3.5
	γ-θ	-0.3	-1.5	0.5	-1.7	-0.4

β2: Beta2 prototype, θ: None, γ: Gamma prototype; negative values represent smaller values for XoSoft compared to None
Angle: peak ankle plantarflexion angle during push-off; Power: maximum total ankle angular joint power; GRF Imp.: anterior ground reaction force impulse (Participant 2 did not have actuation at the left ankle)

IV. Discussion

The increase of peak ankle plantarflexion angle during push-off of walking with XoSoft was a favorable result as it represents a movement pattern that supports a more dynamic push-off, which is necessary for a dynamic walking pattern [1], [6]. However, the increased movement does not directly translate into more total joint power. Participant 1 is able to generate more power with Beta2 and Gamma. The improvements were between 5 and 22%. Previous work has shown a decrease in joint moment generation of 26-38% in people with iSCI compared to healthy [5]. It can be assumed that XoSoft is able to compensate some of the lost function for participant 1. Participant 3 showed small to no effects with Beta2 and reduced power with Gamma, while participant 2 was able to benefit from Gamma but not Beta2.

The ground reaction force impulse is one determining factor during the push-off as it propels the body forward [2]. The increases in GRF impulse are between 4 and 43%. But, decreases (mainly for Gamma) in the range of 2 to 11% were also reported. Based on the combination of reported results, no clear trend on which prototype has more promising effects on the walking mechanics can be concluded. Generally, the actuation strategy of XoSoft can influence the push-off during gait positively, however, not for every person. The participants were only given a short amount of time to familiarize with XoSoft. Consequently, walking with XoSoft may have been more of a challenge than support leading to negative effects of XoSoft for some participants.

No clear trend emerged on which approach for garment design is favorable, as participant 2 seemed to benefit more from Gamma, for participant 3 it was Beta2 that resulted in better outcomes (participant 1 with comparable results for Beta2 and Gamma). The design of the garment is essential regarding the functionality of the actuation (anchor points need to be securely fastened to the leg in order to transfer the energy). It may be the individual's characteristics that determine which design results in a better fit and, therefore, a transfer of energy. Overall, the approach of Gamma with non-custom garments seems promising to follow up as it appears to be capable to serve the intended purpose.

V. Conclusion

Overall, it can be concluded that XoSoft has the potential to support the dynamics of gait during push-off. However, there are no consistent findings yet based on the case-series with three participants. A more systematic approach with larger sample size is needed now to determine the detailed effects of XoSoft on gait mechanics.

References

[1] R. R. Neptune, S. A. Kautz, and F. E. Zajac, "Contributions of the individual ankle plantar flexors to support, forward progression and swing initiation during walking," *J. Biomech.*, vol. 34, pp. 1387–1398, 2001.

[2] S. N. Fickey, M. G. Browne, and J. R. Franz, "Biomechanical effects of augmented ankle power output during human walking," *J. Exp. Biol.*, vol. 221, no. 22, Nov. 2018.

[3] E. Desrosiers, C. Duclos, and S. Nadeau, "Gait adaptation during walking on an inclined pathway following spinal cord injury," *Clin. Biomech.*, vol. 29, no. 5, pp. 500–505, 2014.

[4] A. Pépin, K. E. Norman, and H. Barbeau, "Treadmill walking in incomplete spinal-cord-injured subjects: 1. Adaptation to changes in speed," *Spinal Cord*, vol. 41, no. 5, pp. 257–270, May 2003.

[5] A. Jayaraman *et al.*, "Lower extremity skeletal muscle function in persons with incomplete spinal cord injury," *Spinal Cord*, vol. 44, no. 11, pp. 680–687, Nov. 2006.

[6] G. S. Sawicki, A. Domingo, and D. P. Ferris, "The effects of powered ankle-foot orthoses on joint kinematics and muscle activation during walking in individuals with incomplete spinal cord injury," *J. Neuroeng. Rehabil.*, vol. 3, no. 3, Feb. 2006.

[7] L. N. Awad *et al.*, "A soft robotic exosuit improves walking in patients after stroke," *Sci. Transl. Med.*, vol. 9, no. 400, Jul. 2017.

[8] V. Power, A. de Eyto, B. Hartigan, J. Ortiz, and L. W. O'Sullivan, "Application of a user-centered design approach to the development of XoSoft – A lower body soft exoskeleton," in *Biosystems and Biorobotics*, vol. 22, Springer International Publishing, 2019, pp. 44–48.

[9] J. Ortiz, C. Di Natali, and D. G. Caldwell, "XoSoft - Iterative design of a modular soft lower limb exoskeleton," in *Biosystems and Biorobotics*, vol. 22, Springer International Publishing, 2019, pp. 351–355.

[10] G. Wu *et al.*, "ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion - part I: ankle, hip, spine," *J. Biomech.*, vol. 35, pp. 543–548, Sep. 2002.