Proceedings on Automation in Medical Engineering
Proc AUTOMED, 2026, Vol. 3, No 1, Article ID 2491, 2 Pages

Infinite Science Publishing

Compensatory Posture Modeling in Lower Limb Amputees

T. Krauskopf[1,2], C. Ott[3], G.W. Herget[4], J. Kubosch[4], C. Maurer[2,3], T. Stieglitz[1,2,5], C. Pasluosta[1,2]*

[1] *Laboratory for Biomedical Microtechnology, Department of Microsystems Engineering, University of Freiburg, Freiburg, Germany*
[2] *BrainLinks-BrainTools, University of Freiburg, Freiburg, Germany*
[3] *Department of Neurology and Neuroscience, Faculty of Medicine, Medical Center, University of Freiburg, Freiburg, Germany*
[4] *Department of Orthopaedics and Trauma Surgery, Faculty of Medicine, Medical Center, University of Freiburg, Germany*
[5] *Bernstein Center Freiburg, University of Freiburg, Freiburg, Germany*
[*] *Corresponding author, email: cristian.pasluosta@imtek.uni-freiburg.de*

Abstract: The human body maintains balance using somatosensory, visual, and vestibular inputs. Individuals with lower limb amputations experience balance deficits due to reduced feedback, leading to a reorganization of their balance control system. We applied controlled perturbations to transtibial (TTA) and transfemoral amputees (TFA), and able-bodied controls, while an inverted pendulum model was used to analyze balance control properties. TFA participants exhibited frequency-specific phase deficits without vision and markedly reduced proprioceptive weights despite preserved gain magnitudes, even during eyes-open conditions. These results suggest distinct postural control adaptations in amputees compared to controls.

I. Introduction

The human body continuously adjusts its posture to maintain balance against internal and external perturbations. Minor disturbances are managed using the ankle strategy for stabilization in the anterior-posterior (AP) direction [1]. More challenging situations may call upon the hip strategy [2]. This complex process relies on somatosensations (proprioception and tactile feedback), vision, and the vestibular system. Somatosensory information is the fastest and most dominant input, accounting for approximately 70% of balance control, while vision and vestibular inputs provide the remaining 10% and 20%, respectively [3].

Individuals with lower limb amputations face significant balance impairments. The loss of ankle strategy control and limited sensory feedback often result in an increased load on their remaining intact leg, leading to compensatory movements and altered center of pressure (COP) patterns [4]. These biomechanical changes force amputees to reorganize their balance control systems, relying more heavily on visual and vestibular feedback [5].

In this work, we applied controlled balance perturbation and measured the body's response to develop a transfer function and infer properties of the balance control system of amputees. We used an inverted pendulum model to identify the proportion of proprioceptive feedback, the neural delays, and how different balance strategies are employed in this population [3].

II. Material and methods

II.I. Participants

Seven individuals with a unilateral transtibial amputation (TTA, 57 ± 27.03 yrs.; 179.20 ± 4.70 cm; 79.94 ± 8.72 kg), seven individuals with a unilateral transfemoral amputation (TFA, 49 ± 26,65 yrs.; 186.60 ± 8.19 cm; 74.42 ± 7.42 kg) and 19 able-bodied individuals (57 ± 17.44 yrs.; 176.09 ± 9.78 cm; 72.89 ± 12.94 kg) participated in this study, which was approved by the University of Freiburg's ethics committee (21-1245 and 24-1444_1-S1). All participants provided informed consent before participating in this study.

II.II. Data Collection

Participants stood on a motorized force platform (Kistler 9286, Winterthur, Switzerland) that rotated in the AP direction in a pseudorandom ternary sequence of 0.5° or 1°. Trials lasted 60 seconds and were performed both with eyes open (EO) and eyes closed (EC). A motion capture system (The Captury GmbH, Saarbrücken, Germany) recorded kinematic data at 100 Hz.

II.III. Transfer Function and Model Fitting

The platform rotation stimulus ($\theta_{Platform}(f)$) was used as the input signal and the respective body segment angles ($\theta_{COM}(f)$) were used as output to estimate a transfer function $H_{exp}(f)$ (1).

$$H_{exp}(f) = \frac{\theta_{COM}(f)}{\theta_{Platform}(f)} \quad (1)$$

We fitted a neuromechanical model representing the transfer function from platform rotation to center of mass (COM) angle (2).

$$H(s) = \frac{(Wp \cdot PIDTD + Kpas \cdot s + Bpas \cdot s^2)}{(s \cdot BI + PIDTD + Kpas \cdot s + Bpas \cdot s^2)} \qquad (2)$$

In (2), an inverted pendulum model represented the body dynamics ($BI = Js^2 - mgh$), with the moment of inertia (J) and gravitational restoring torque (mgh) capturing physiological constraints of upright stance. $PIDTD = (K_D s^2 + K_P s + K_I) \cdot e^{-TDs}$ represented a proportional, integral and derivative (PID) neural controller with time delay. $Kpas$ was the passive stiffness and $Bpas$ was the passive damping. TD represented the sensorimotor processing delay in seconds and Wp the sensory weighting (proprioceptive contribution). Initial estimates were: $K_I = 100$ (fixed), $K_P = 950$, $K_D = 250$, $Wp = 0.8$, $TD = 0.15\,s$, $Kpas = 90\,\mathrm{Nms/rad}$ (fixed) and $Bpas = 60\,\mathrm{Nms/rad}$ (fixed). The *fmincon* function in MATLAB implemented the interior-point algorithm to minimize the normalized complex transfer function error.

III. Results and discussion

The results showed a clear difference between controls and transtibial and transfemoral amputees in gain across visual conditions and perturbation angles, but these differences were less markedly in the phase (Fig. 1). These results suggest distinct responses to the perturbation stimuli, meaning an adapted postural control system after following a lower limb amputation. The able-bodied controls presented an increased gain overall, which suggests increased reaction to stimuli than amputees. Differences in model parameters were also observable between controls and amputees (Table 1), suggesting changes in the overall neural control of their COM.

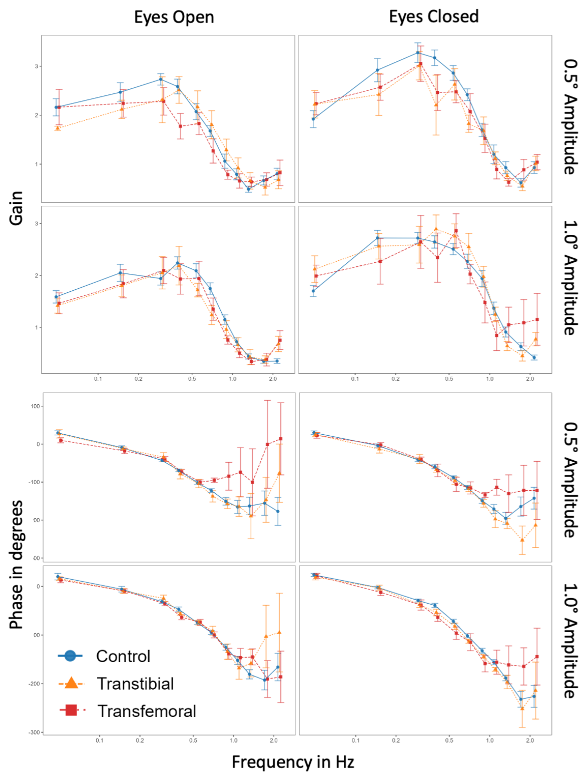

Figure 1: Gain and phase results (mean and SE).

Table 1: Results of the model. Mean (SE).

Grp.	C	SA	K_P/mgh	K_D/mgh	W_P	TD(s)
Ctrl	EO	0.5	1.31 (0.17)	0.36 (0.10)	0.68 (0.23)	0.17 (0.06)
		1	1.38 (0.20)	0.41 (0.09)	0.58 (0.12)	0.16 (0.04)
	EC	0.5	1.34 (0.25)	0.40 (0.07)	0.89 (0.18)	0.18 (0.06)
		1	1.43 (0.19)	0.43 (0.06)	0.84 (0.12)	0.17 (0.03)
TTA	EO	0.5	1.35 (0.37)	0.46 (0.07)	0.76 (0.26)	0.17 (0.09)
		1	1.36 (0.23)	0.46 (0.12)	0.48 (0.20)	0.18 (0.07)
	EC	0.5	1.30 (0.31)	0.43 (0.09)	0.85 (0.15)	0.19 (0.06)
		1	1.39 (0.23)	0.43 (0.07)	0.80 (0.13)	0.18 (0.05)
TFA	EO	0.5	1.14 (0.11)	0.44 (0.12)	0.30 (0.22)	0.23 (0.07)
		1	1.33 (0.10)	0.43 (0.08)	0.45 (0.13)	0.17 (0.05)
	EC	0.5	1.31 (0.10)	0.46 (0.10)	0.79 (0.26)	0.16 (0.05)
		1	1.36 (0.18)	0.40 (0.10)	0.67 (0.21)	0.17 (0.06)

IV. Conclusions

We modeled postural control in lower limb amputees by an inverted pendulum and a delayed PID controller. Kinematic data was recorded during rotational perturbations of the ankle joint. We observed significant changes in the transfer function of amputees with respect to controls and neural parameters of the modelled control system.

Acknowledgments

This work was supported by the German Research Foundation (N°. 505063807) and BrainLinks-BrainTools, funded by the German Research Foundation (N° EXC 1086) and is currently funded by the Federal Ministry of Economics, Science and Arts of Baden-Württemberg within the sustain-ability program for projects of the excellence initiative II.

Author's statement

Conflict of interest: Authors state no conflict of interest.

References

[1] G. M. Blenkinsop, M. T. G. Pain, and M. J. Hiley, 'Balance control strategies during perturbed and unperturbed balance in standing and handstand', *R Soc Open Sci*, vol. 4, no. 7, 2017, doi: 10.1098/rsos.161018.

[2] C. F. Runge, C. L. Shupert, F. B. Horak, and F. E. Zajac, 'Ankle and hip postural strategies defined by joint torques', Gait Posture, vol. 10, no. 2, 1999, doi: 10.1016/S0966-6362(99)00032-6.

[3] R. J. Peterka, 'Sensorimotor integration in human postural control', J Neurophysiol, vol. 88, no. 3, 2002, doi: 10.1152/jn.2002.88.3.1097.

[4] C. R. Claret et al., 'Neuromuscular adaptations and sensorimotor integration following a unilateral transfemoral amputation', J Neuroeng Rehabil, vol. 16, no. 1, p. 115, 2019, doi: 10.1186/s12984-019-0586-9.

[5] K. Fuchs et al., 'Influence of Augmented Visual Feedback on Balance Control in Unilateral Transfemoral Amputees', Front Neurosci, vol. 15, p. 1198, 2021, [Online]. Available: https://www.frontiersin.org/article/10.3389/fnins.2021.727527