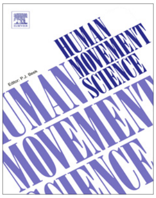
Human Movement Science 40 (2015) 248–263

Contents lists available at ScienceDirect

Human Movement Science

journal homepage: www.elsevier.com/locate/humov



Psychophysiological response to cognitive workload during symmetrical, asymmetrical and dual-task walking

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ARTICLE INFO

PsycINFO classification:
2560
4100

Keywords:
Psychophysiological response
Cognitive workload
(A)symmetrical walking
Performance
Dual-task

ABSTRACT

Walking with a lower limb prosthesis comes at a high cognitive workload for amputees, possibly affecting their mobility, safety and independency. A *biocooperative* prosthesis which is able to reduce the cognitive workload of walking could offer a solution. Therefore, we wanted to investigate whether different levels of cognitive workload can be assessed during symmetrical, asymmetrical and dual-task walking and to identify which parameters are the most sensitive. Twenty-four healthy subjects participated in this study. Cognitive workload was assessed through psychophysiological responses, physical and cognitive performance and subjective ratings. The results showed that breathing frequency and heart rate significantly increased, and heart rate variability significantly decreased with increasing cognitive workload during walking ($p < .05$). Performance measures (e.g., cadence) only changed under high cognitive workload. As a result, psychophysiological

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http://dx.doi.org/10.1016/j.humov.2015.01.001

measures are the most sensitive to identify changes in cognitive workload during walking. These parameters reflect the cognitive effort necessary to maintain performance during complex walking and can easily be assessed regardless of the task. This makes them excellent candidates to feed to the control loop of a *biocooperative* prosthesis in order to detect the cognitive workload. This information can then be used to adapt the robotic assistance to the patient's cognitive abilities.

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1. Introduction

Ambulating with a transfemoral prosthesis is not only associated with high metabolic costs (Hoffman, Sheldahl, Buley, & Sandford, 1997), it also requires a considerable larger amount of cognitive resources compared to walking in individuals with intact limbs (Geurts & Mulder, 1994; Geurts, Mulder, Nienhuis, & Rijken, 1991; Heller, Datta, & Howitt, 2000; Hofstad et al., 2009; Williams et al., 2006). Some of these cognitive resources are devoted to compensate for the loss of motor control at the amputated joint(s). This loss requires new strategies, such as reliance on stump muscles and hip or trunk compensatory mechanisms, to control motor actions (Heller et al., 2000). Another part is lost due to the increased use of vision to compensate for the loss of somatosensory feedback from the amputated limb (Krewer et al., 2007; Williams et al., 2006; Witteveen, de Rond, Rietman, & Veltink, 2012). Consequently, walking with a transfemoral prosthesis involves higher cognitive demands, often leaving not enough cognitive capacity available to perform secondary information-processing tasks such as attending a conversation while walking (Heller et al., 2000; Williams et al., 2006). Additionally, increased cognitive workload can also endanger the primary motor task: for instance obstacle avoidance or uneven terrain negotiation during walking can be impeded. Moreover, some studies already showed that limping-like walking significantly increased the risk of falling in amputees (Duysens, Potocanac, Hegeman, Verschueren, & McFadyen, 2012).

A solution could be contained in recently developed physiological computing systems which 'sense, analyze and react' to the cognitive state of the user (Rodriguez Guerrero, Fraile Marinero, Perez Turiel, & Munoz, 2013). These systems are designed to promote the performance efficiency of the user and operate through a *biocybernetic* loop which monitors the users' cognitive state, reacts appropriately and tunes its functioning in an adaptive closed loop (Serbedzija & Fairclough, 2009). Such a *biocybernetic* control loop could also be incorporated in an active prosthesis in order to monitor and reduce the cognitive workload of the amputee during locomotor tasks (Deeny, Chicoine, Hargrove, Parrish, & Jayaraman, 2014). As for other physiological computing systems, it will allow the amputee and the prosthesis to interact in a collaborative symbiotic manner resulting in a higher motor performance at a lower cognitive workload (Serbedzija & Fairclough, 2009).

Measuring cognitive workload has not yet been standardized in dynamic situations such as walking. A major challenge in these situations is that effects of the physical workload may overshadow effects of the cognitive workload (Novak, Mihelj, & Munih, 2010). Previous studies have mainly focused on performance and subjective parameters to assess cognitive workload in dynamic situations, mostly under dual-task paradigms (Al-Yahya et al., 2011; Kline, Poggensee, & Ferris, 2014; Nascimbeni, Minchillo, Salatino, Morabito, & Ricci, 2014; Patel & Bhatt, 2014). Yet, this could be inadequate, for example, walking performance of an amputee can be good, but this can come at a high cognitive effort, and thus a high cognitive workload. Or subjective measures can be intentionally manipulated or affected by subject characteristics (e.g., attitude, memory capacity, ... etc.) and give a distorted picture of cognitive workload (Dirican & Göktürk, 2011; HFM-056/TG-008, 2004). Thus, to adequately assess cognitive workload, not only performance parameters and subjective ratings should be taken into account, but also the cognitive effort, i.e., the investment a subject puts in the