Human Movement Science xxx (2013) xxx–xxx

ELSEVIER

Contents lists available at ScienceDirect

Human Movement Science

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

Multi-dimensional coordination in cross-country skiing analyzed using self-organizing maps

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A R T I C L E I N F O

Article history:
Available online xxxx

PsycInfo classification:
4160
3720
2330

Keywords:
Attractors
Coordination dynamics
Cross-country skiing
Double poling
Multi-dimensional coordination
Redundancy
Self-organizing maps

A B S T R A C T

This study sought to ascertain how multi-dimensional coordination patterns changed with five poling speeds for 12 National Standard cross-country skiers during roller skiing on a treadmill. Self-organizing maps (SOMs), a type of artificial neural network, were used to map the multi-dimensional time series data on to a two-dimensional output grid. The trajectories of the best-matching nodes of the output were then used as a collective variable to train a second SOM to produce attractor diagrams and attractor surfaces to study coordination stability. Although four skiers had uni-modal basins of attraction that evolved gradually with changing speed, the other eight had two or three basins of attraction as poling speed changed. Two skiers showed bi-modal basins of attraction at some speeds, an example of degeneracy. What was most clearly evident was that different skiers showed different coordination dynamics for this skill as poling speed changed: inter-skier variability was the rule rather than an exception. The SOM analysis showed that coordination was much more variable in response to changing speeds compared to outcome variables such as poling frequency and cycle length.

1. Introduction

Double poling is one of the fundamental techniques used in classic cross-country skiing. The propulsive forces are synchronously transmitted through two poles during ground contact initiating with

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0167-9457/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.humov.2013.08.005

a body weight assisted pull and transitioning to a final push (Smith, 2002), both together characterizing a stretch-shortening cycle in arm and shoulder extensor muscles enhancing poling power (Lindinger, Müller, & Rapp, 2009). The poling phase is followed by the recovery or arm swing phase in which the whole body is repositioned for the next pole plant. The use of double poling has increased in the last 20 years to become an important technique in cross-country ski racing. New race disciplines, improved training methods and upgraded skiing equipment lead to significant changes in the kinematic, kinetic and electromyographic double poling patterns (Holmberg, Lindinger, Stöggl, Eitzlmair, & Müller, 2005).

Two fundamental questions arise about this technique from a biomechanics perspective. Firstly, how do modern elite cross-country skiers control double poling speeds; secondly, how do skiers coordinate their body movements to change poling speed. The former question has been addressed previously, most notably by Lindinger, Stöggl, Müller, and Holmberg (2009), who also provided an overview of previous related work. To date, however, little attention has been paid to how cross-country skiers coordinate their movements. Cignetti, Schena, Zanone, and Rouard (2009) used joint couplings in classical cross-country skiing to determine changes in coordination associated with skiing on different slopes. They reported that changing slopes brought about transitions between attractor states of coordination. Like many studies of human movement coordination, however, the complex interaction of the many biomechanical components was reduced to an analysis of low-dimensional comparisons (e.g. Burgess-Limerick, Shemmell, Barry, Carson, & Abernethy, 2001; Wagenaar & van Emmerik, 2000).

Generally, coordination involves the assemblage of the underlying degrees of freedom in order to form stable movement patterns which are adaptable to the potentially changing constraints of the task. In cross-country skiing, coordination involves the movements of the joints of both legs and arms and the trunk, as well as the main muscles of those joints, and how those joint movements relate to the pole and ski forces. Such coordination has been characterized as multi-dimensional coordination (e.g. Bartlett, O'Donovan, Kennedy, & Saini, 2012) or multi-articular (e.g. Chow et al., 2009) or multi-joint (e.g. Liu, Whitall, & Kepple, 2013) coordination. Previous biomechanical studies determined numerous relevant kinematic, electromyographic and kinetic key variables to describe and analyze the complexity and different specific aspects of the double poling technique (Holmberg et al., 2005, Holmberg, Lindinger, Stöggl, Björklund, & Müller, 2006; Komi & Norman, 1987; Lindinger & Holmberg, 2011; Lindinger, Müller, et al., 2009; Lindinger, Stöggl, et al., 2009; Stöggl, Lindinger, & Müller, 2006) which can serve as appropriate input variables for a multi-dimensional coordination analysis of double poling under the influence of a control parameter such as skiing speed. The study of multi-dimensional coordination requires a completely different approach from pair wise joint or segment coordinations, usually studied using angle-angle diagrams, discrete or continuous relative phase, or cross correlation functions (as outlined in Bartlett & Bussey, 2012).

Several other approaches for studying multi-dimensional coordination exist; notable approaches have been Principal Components Analysis (PCA), Uncontrolled Manifold (UCM) and Support Vector Machines (SVM). Both, PCA and UCM, investigate the covariation of certain variables, although UCM provides information with respect to the task goal (Rein, 2012). PCA has been used frequently in studies of human movement, often looking at how the role of dominant variables in describing the variance in the data may change in response to changing task constraints (e.g. Post, Daffertshofer, & Beek, 2000). Analyses using UCM look to find certain time-series variables that correlate with the outcome or the goal of the task and, therefore, identify which variables are controlled (see Scholz & Schöner, 1999). SVM performs a binary classification on two-class labeled data (e.g. presence or absence of fatigue; Janssen et al., 2011) by identifying a hyperplane which best partitions the data classes. For the purposes of the current study we chose self-organizing maps (SOMs: a type of artificial neural network: see Kohonen, 2001) so that we could visualize the evolving multi-dimensional coordination throughout the movement. The PCA and UCM approaches reduce the dimensionality to fewer dimensions, although not necessarily to the extent of being visualizable. SVM is a supervised method and we opted to not introduce possible a priori bias by classifying the data.

Lamb, Bartlett, and Robins (2010) used SOMs in their study of three different basketball shots – free throw, jump shot and three-point shot – by four skilled players in basketball, and found clear differences in coordination patterns, visualized by U-matrices, between players and shots. Lamb, Bartlett, and Robins (2011) studied golf chipping from 4 m and in 4 m increments up to 24 m by four

Please cite this article in press as: Lamb, P. F., et al. Multi-dimensional coordination in cross-country skiing analyzed using self-organizing maps. *Human Movement Science* (2013), http://dx.doi.org/10.1016/j.humov.2013.08.005