Human Movement Science 55 (2017) 156–171

Contents lists available at ScienceDirect

Human Movement Science

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

The proximal-to-distal sequence in upper-limb motions on multiple levels and time scales

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ARTICLE INFO

Keywords:
Throwing
Striking
Reaching
Motor control
Dynamical system
Constraints

ABSTRACT

The proximal-to-distal sequence is a phenomenon that can be observed in a large variety of motions of the upper limbs in both humans and other mammals. The mechanisms behind this sequence are not completely understood and motor control theories able to explain this phenomenon are currently incomplete. The aim of this narrative review is to take a theoretical constraints-led approach to the proximal-to-distal sequence and provide a broad multidisciplinary overview of relevant literature. This sequence exists at multiple levels (brain, spine, muscles, kinetics and kinematics) and on multiple time scales (motion, motor learning and development, growth and possibly even evolution). We hypothesize that the proximodistal spatiotemporal direction on each time scale and level provides part of the organismic constraints that guide the dynamics at the other levels and time scales. The constraint-led approach in this review may serve as a first onset towards integration of evidence and a framework for further experimentation to reveal the dynamics of the proximal-to-distal sequence.

1. Introduction

As early as the 17th century, golf practitioners were aware of the phenomenon of proximal-to-distal (P-D-) sequencing, captured in the following verse:

> *"All motions with the strongest joynts performe. Lett the weaker second and perfect the same. The stronger joynt its motion first must end. Before the nixt to move in the least intend."* (Kinkaid, 1687 cited in Herring & Chapman, 1992).

In the following sections, we will provide a more detailed discussion of the biomechanical principles, but a general notion of the P-D-sequence is usually given in kinematic terms where the motion is initiated by the proximal, larger, slower rotating segments with the more distal segments lagging behind their proximal neighbors due to inertia. When the proximal segments reach their maximal velocity, the linked distal segment starts to accelerate. As a proximal segment's velocity decreases, this deceleration causes an inertial effect, propelling the linked distal segment forward in the direction of motion. For instance, in overhand throwing, when the pelvis reaches its maximal forward rotation velocity, the trunk starts to accelerate forward and this acceleration is aided by the deceleration or backward acceleration of the pelvis. The same principle then applies between trunk and upper arm, upper and lower arm and lower arm and hand. The more distal segments with their lower masses and moments of inertia will thus rotate faster; the same notion is applicable to lower limb motions. Hitherto, a multitude of research from various domains has been conducted on motions with P-D-

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http://dx.doi.org/10.1016/j.humov.2017.08.009
Received 26 January 2017; Received in revised form 6 June 2017; Accepted 14 August 2017
Available online 21 August 2017
0167-9457/

sequencing without a complete mechanism or motor control theory emerging from it.

1.1. Definitions and methodological issues

The body of evidence on the P-D-sequence is large, but confusing due to unclear terminology and a large variety of variables on multiple levels of analysis. We used only kinematic terms in the simple sketch above and ignored the role of muscles and the central nervous system, which is obviously incomplete. This notion cannot serve as a definition of the phenomenon, nor is there any agreed-upon version of a definition, making it hard to compare empirical results. Besides P-D-sequencing (Putnam, 1993), other terminology has been used to describe the same phenomenon, including 'acceleration-deceleration principle' (Plagenhoef, 1971), 'summation of speed principle' (Bunn, 1972), 'kinetic link principle' (Kreighbaum & Barthels, 1985), 'kinematic chain' (Bartlett, 1999) and 'whip-like movement' (Zatsiorsky, 2002). Marshall and Elliott (2000) even briefly referred to the term 'grand plan' to explain different throwing and striking motions. We argue that the terminology of P-D-sequencing is more correct however, because (1) it puts the focus on the main spatiotemporal direction of the motion, (2) the phenomenon is not confined to motions where end-effector speed should be maximized (see Table 1) and (3) P-D-sequencing is not confined to a single level of description, i.e. the kinematic/kinetic level in the other synonyms (see Section 5).

The defining factor for evidence on P-D-sequencing on any level of description should be a time difference for a distal degree of freedom's activity with respect to its more proximal neighbors. Two issues exist with respect to the definition of timing itself. First, the P-D-sequence of kine(ma)tics or muscle activity can be studied in terms of initiation and in terms of an extremum with sometimes contradictory results between both definitions (e.g. van den Tillaar & Ettema, 2009b). Secondly, it can be defined as a difference in timing between proximal and distal joint activity (Southard, 2009), absolutely with respect to a certain key-point like ball release (Wagner, Pfusterschmied, von Duvillard, & Müller, 2012) or relative timing can be used as a percentage of total movement time (Liu, Leigh, & Yu, 2010). In the latter case, different studies will need to carefully choose the same start- and end-points to be able to compare results. This results in six possible definitions of timing to examine P-D-sequencing. No correct answers are available to these methodological issues, but we do observe that most researchers report extrema and absolute timing.

1.2. Examples of P-D-sequencing and aim of the review

Given the broad range of motions exhibiting this sequence (see Table 1), all variations might be related to a basic strategy of motor control that takes these specific initial conditions, task-specific performance criteria (speed, accuracy, timing, …) and possible subconscious optimization criteria (injury prevention, energy minimization, …) into account. A single criterion (e.g. maximal end-effector speed) will thus not be able to explain the P-D-sequence where other criteria apply. Other constraints are necessary to explain its ubiquity. The common origin of this phenomenon may possible be found in the development and evolution of our species, but how all the specific (bio-)mechanical and neurological mechanisms and constraints interact to produce this typical sequence in a great

Table 1
Examples of motions with evidence for a proximal-to-distal sequence.

Motion	Reference	Level of analysis
Striking		
Volleyball spike	Wagner et al. (2012)	Kinematics
Tennis serve	Bahamonde (2000)	Angular Momentum
	Wagner et al. (2012)	Kinematics
Punching	VencesBrito et al. (2011)	Electromyography and Kinematics
Field hockey drag flick	Ibrahim, Faber, Kingma, and van Dieën (2016)	Kinematics
Throwing		
Team handball	van den Tillaar and Ettema (2009)	Kinematics
	Wagner et al. (2012)	Kinematics
	Serrien et al. (2015)	Kinematics
Baseball	Hirashima et al. (2002)	Electromyography
	Hirashima et al. (2008)	Kinetics
Cricket	Ferdinands et al. (2013)	Kinetic Energy
Water polo	Yaghoubi et al. (2015)	Electromyography
Javelin	Liu et al. (2010)	Kinematics
Shot put	Coh, Stuhec, and Supej (2008)	Kinematics and Kinetics
Other		
Piano playing	Furuya and Kinoshita (2007)	Kinematics
Cello and violin playing	Verrel, Pologe, Manselle, Lindenberger, and Woollacott (2013a, 2013b)	Kinematics
Stone knapping	Williams, Gordon, and Richmond (2010), Williams, Gordon and Richmond (2014)	Kinematics
Reaching	Hatsopoulos et al. (2011)	Kinematics and Motor Cortex
Lower limb actions[*]		
Instep kick soccer	Naito, Fukui, and Maruyama (2012)	Kinetics
Round kick taekwondo	Estevan, Falco, Silvernail, and Jandacka (2015)	Kinematics

* This review focusses on the upper limb, but lower limb actions also show typical P-D-sequencing.