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Modelling the learning of biomechanics and visual planning for decision-making of motor actions

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ABSTRACT

Recent experiments showed that the bio-mechanical ease and end-point stability associated to reaching movements are predicted prior to movement onset, and that these factors exert a significant influence on the choice of movement. As an extension of these results, here we investigate whether the knowledge about biomechanical costs and their influence on decision-making are the result of an adaptation process taking place during each experimental session or whether this knowledge was learned at an earlier stage of development. Specifically, we analysed both the pattern of decision-making and its fluctuations during each session, of several human subjects making free choices between two reaching movements that varied in path distance (target relative distance), biomechanical cost, aiming accuracy and stopping requirement. Our main result shows that the effect of biomechanics is well established at the start of the session, and that, consequently, the learning of biomechanical costs in decision-making occurred at an earlier stage of development. As a means to characterise the dynamics of this learning process, we also developed a model-based reinforcement learning model, which generates a possible account of how biomechanics may be incorporated into the motor plan to select between reaching movements. Results obtained in simulation showed that, after some pre-training corresponding to a motor babbling phase, the model can reproduce the subjects' overall movement preferences. Although preliminary, this supports that the knowledge about biomechanical costs may have been learned in this manner, and supports the hypothesis that the fluctuations observed in the subjects' behaviour may adapt in a similar fashion.

1. Introduction

Significant progress has been recently made to determine the implication of the motor apparatus in the preparation and execution of motor movements. First, in the context of goal-directed movements, prior postural adjustments have been described as a method to bring the muscular-skeletal conditions to an initial state, favourable for the execution of the intended movement (Bottaro et al., 2008; Lakie and Loram, 2006; Lakie et al., 2003; Morasso and Sanguinetti, 2002). Second, reaching movements around pointy obstacles also exhibited a bias towards trajectories exhibiting a larger resistance to potential perturbations perpendicular to the trajectory (Sabes et al., 1998; Sabes and Jordan, 1997). Third, a series of recent experiments have shown that not only are some estimates of the biomechanical cost of future trajectories calculated in anticipation of movement onset (Dounskaia et al., 2011), but also that these costs influence the selection of a reaching movement over another (Cos et al., 2011). Furthermore, variations of the same task with different levels of end-point control also showed that biomechanical factors were most influential in the absence of precise instruction about the movement, e.g., when the movements were most unconstrained, implying that biomechanical factors associated to motor movements are highly context-dependent and interact with the subjective desirability of potential actions (Cos et al., 2012).

Hence, although this proved biomechanical costs to be calculated during movement preparation, it remains to be tested whether this information is gained in a gradual manner, dependent on the task specificities, and necessitates of significant training, or by the contrary, whether it had been learned at an earlier development state. Although these goals extend beyond the scope of this paper, here we propose to initiate that path by assessing the dynamics of the influence of biomechanics on decision-making during the course of an experimental session. In other words, here we investigate to what extent is knowledge about the structure of the motor apparatus learned or adapted during the task, and to what extent this has been learned at an earlier stage of

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development. Furthermore, we also developed a theoretical model, aimed at reproducing the patterns of decision incorporating the factor of biomechanics as shown by (Cos et al., 2011), as well as the variability exhibited on a single individual basis. The model is trained by reinforcement learning (RL) (Sutton and Barto, 1998) on the basis of the costs and benefits associated to the execution of each movement. A key principle of the model is that the learning of such costs and benefits is based on an internal model, which previous research has stressed to be of crucial importance for the generation of goal-directed movements (Kawato, 1999). Similar to previous models of motor decision-making (Doya et al., 2002), here the internal model is learned as the combination of a *reward function*, and a *state-action transition function* in a model-based RL framework. We illustrate the principle of learning to incorporate biomechanics within such internal model by generalising the so-called *reward function* in a manner that takes into account both costs and benefits (Sutton, 1991), and by alternating a phase for learning the internal model – here through motor babbling – with a phase for making decisions based on this internal model (Sutton, 1990). In a straightforward fashion, the simulated results exhibit a remarkable similarity with the results obtained experimentally, therefore supporting the hypothesis that the influence of factors related to the motor apparatus on movement preparation may be learnt via reinforcement, together with processes of early motor adaptation.

2. Materials and methods

2.1. Psychophysics experiment

2.1.1. Characterization of biomechanics

Several factors may be associated to the notion of biomechanics: muscle viscoelastic properties, passive inertia, interaction torques, or muscle energy. However, because the primary goal was to assess whether some of these factors were included into the motor plan and whether they influenced decision-making, we used the alignment of the end-point trajectory with the axes of the planar ellipse of mobility/admittance as our metric of biomechanics (Hogan, 1985a,b,c). Although this is approximate in so far it does not include interaction torques, it is a reasonable first order

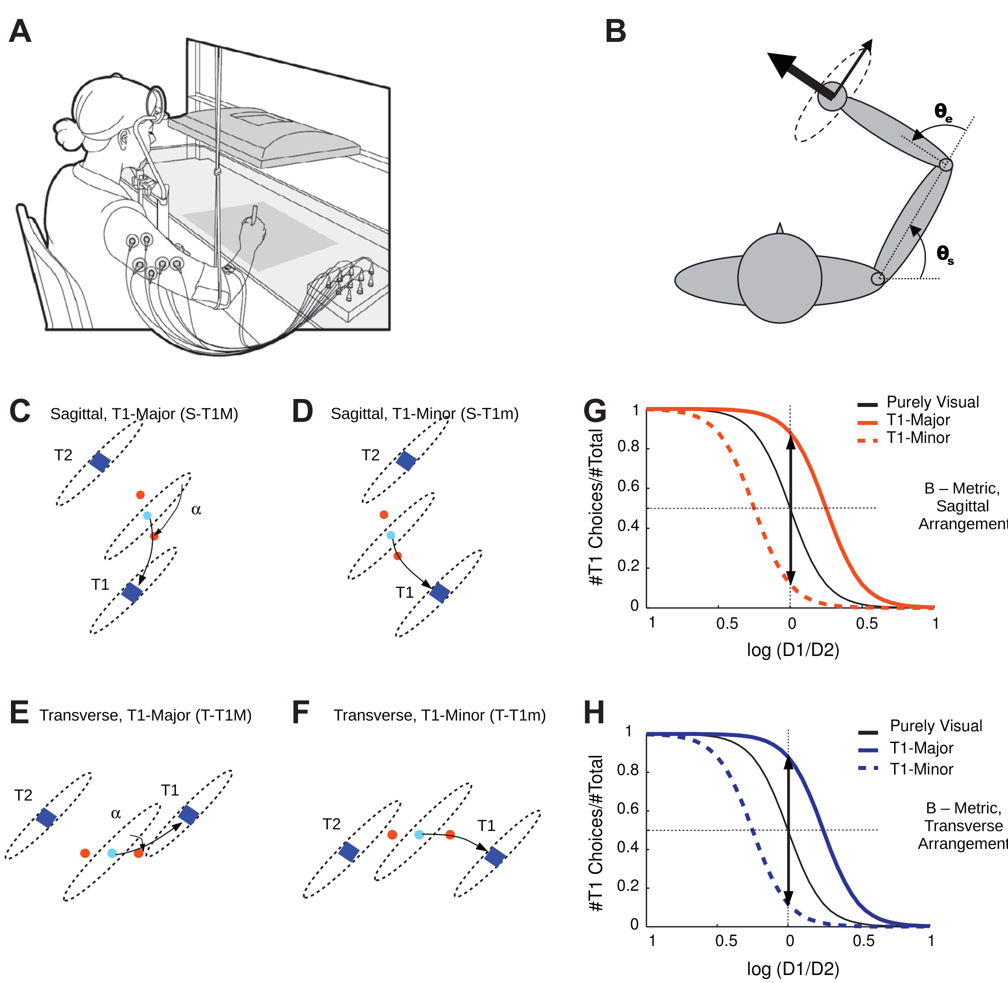

Fig. 1. Experimental paradigm. Adapted with permissions from (Cos et al., 2011). (A) Subject seated at the apparatus with her head in a chin rest and elbow in a sling that suspends the forearm approximately parallel to the digitizer surface. (B) Definition of joint angles and the mobility/admittance ellipse at the hand (dashed line). The thick arrow depicts the large force required to accelerate the hand away and to the left, while the thin arrow depicts a smaller force required to produce the same acceleration away and to the right. (C–F) The four arrangements of targets (blue dots), and via-points (red dots) with respect to the starting circle (cyan dot). Dashed lines depict mobility ellipses at the origin and end of movements. Arrows show example trajectories to target T1. Note that in the T1-Major arrangements, the trajectory arrives at T1 along the major axis of the mobility ellipse, whereas for T1-minor it arrives along the minor axis. (G) Predicted choice patterns for the sagittal stimulus arrangements (C,D). The *x*-axis is the log of the ratio of path distances (D) to T1 vs. T2, and the *y*-axis is the number of choices made to T1. If subjects prefer to arrive along the major axis of the mobility ellipse then the choice function for the T1-Major arrangement (solid line) should be shifted to the right of the choice function for T1-minor arrangement. If subjects do not take biomechanics into account then the choice functions should be identical (black line). (H) Predictions for the transverse arrangements (E,F), same format. The B – Metric is the vertical distance between T1M and T1m preference curves for the case of equal relative distances.