Anticipatory postural adjustments in reach-to-grasp: Effect of object mass predictability

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Anticipatory postural adjustments (APAs) are thought to compensate for upcoming and predictable perturbations before they occur, e.g., a backward shift of the body center of pressure (COP) before raising the arm. When the goal of arm movements is to reach, grasp, and manipulate an object, predicting the effect of raising the arm on body COP before reach onset could incorporate the properties of the object to be lifted, as both will affect postural control during reaching and object manipulation. Alternatively, the central nervous system (CNS) might use separate APAs to compensate for the effect of arm raising from raising the arm and object. To distinguish between these two scenarios, we asked subjects to reach, grasp, and lift an object whose mass (100 g, 750 g, or 1400 g) was either constant across trials or variable from trial to trial (‘predictable’ and ‘unpredictable’ condition, respectively). We hypothesized that object mass would affect the magnitude of APAs in the predictable condition before the onset of object lift but not before the initial arm onset. We also expected COP variability following object lift to be reduced as a result of APAs. For the unpredictable condition, we expected ‘default’ APAs that would minimize postural perturbation following object lift. We found that both magnitude and timing of APAs were modulated as a function of predictable object mass prior to contact, rather than at the onset of the reaching movement. Specifically, COP position moved forward with increasing object load (p < 0.05) and peak COP velocity related to object contact occurred significantly early for heavier loads (p < 0.05). For the random condition, the COP position and timing at all loads resembled that associated with larger predictable loads. These findings suggest that modulating COP to a future event might be more accurate when timed to temporally close events, thus potentially reducing the computational load as well as risks of prediction errors. Additionally, our results might suggest limitations in the predictive capability of the CNS in relation to ‘how far in the future’ it can go when predicting the consequences of planned actions.

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Anticipatory control mechanisms play an important role in a variety of everyday movements ranging from grasping [10,11,18] to whole body movements, e.g., landing (see [25] for review). Classic examples of whole body anticipatory control are anticipatory postural adjustments (APAs) performed prior to the onset of a limb movement [3,5,7,19]. It is thought that the functional role of anticipatory control is to compensate for upcoming and predictable perturbations before they occur, hence bypassing long delays associated with feedback. Therefore, anticipating that the body center of pressure (COP) will shift forward during lifting of the arm results in a shift of the body COP backwards before the arm movement onset [4,12,24].

The ability to predict the effects of upper limb movements on postural control relies on knowing the static and dynamic properties of the limb, i.e., an internal model [8,14]. Often, however, the goal of arm movements is to reach, grasp, and manipulate an object. In this scenario, an internal model of the arm has to incorporate the properties of the object, e.g., mass or mass distribution, as both will affect the control of posture throughout arm movement and subsequent object manipulation. It should be noted that, unlike the properties of the upper limb, the properties of an object might not be always predictable prior to manipulation, thus challenging the central nervous system’s (CNS) ability to program suitable APAs to anticipate movement of the arm with the object. Although the effect of predictability of object properties on grasp planning have been extensively studied [13,18,27], how the CNS organize APAs as function of object property predictability when planning reach-to-grasp movements has not been investigated.

The present study was designed to investigate body COP during movement of the upper limb consisting of reaching, grasping, and lifting an object. The mass of the object was either constant across trials or variable from trial to trial (‘predictable’ and ‘unpredictable’ condition, respectively). Two possible outcomes can be envisioned, depending on whether APAs occurring before the onset

Signals from the platform were sampled at 200 Hz (12-bit A/D conversion) and filtered with a zero phase, second-order Butterworth filter (5 Hz lowpass cut-off frequency). In addition, to detect the onset and the end of arm movement and the time at which the hand grasps the object, two accelerometers (DE-ACCM2G 2 axes ±2 g sense range Accelerometer, Dimension Engineering, Akron, OH, USA) were attached on the right hand and on the object, respectively. The output of the accelerometer on the hand was used for COP data alignment. The accelerometer on the object was used to estimate contact of the hand with the object. The first detectable change in the output of the accelerometer occurred along the horizontal axis (X axes in Fig. 1) followed by a second acceleration along the vertical direction signaling object lift onset (Y axes in Fig. 1). The first event was defined as object contact.

To assess the effects of different loads and predictability conditions on postural adjustments, a set of temporal and spatial parameters of the COP traces was analyzed. As illustrated in the first panel of the top row of Fig. 2, three time points were selected from the COP velocity profile to evaluate time interval changes in relation to the onset of arm movement or to the time of the object contact. The three points are defined as follows: (1) onset of COP backward displacement; (2) the first peak velocity during COP forward displacement; (3) the first minimum in COP velocity occurring after object contact indicating the onset of a subsequent acceleration caused by the load. When the third time epoch could not be defined automatically by software, this time was assessed visually; in the case of absent clear peaks, we considered the point where a change of slope occurred. However, visual detection of the third epoch was required only in 10% of trials.

In addition, the COP spatial positions at the time of movement onset, at the time of object contact and at the end of the arm movement were determined.

Temporal and spatial variables were analyzed using a repeated measures two-way analysis of variance (ANOVA) with “Load” (100 g, 750 g, and 1400 g) and “Predictability condition” (predictable vs. unpredictable) as factors. In the case of significant main effects, post-hoc analysis was performed by means of t-tests using the standard Bonferroni’s corrections (α level of p < 0.05).

Fig. 2 shows the time course of whole body center of pressure velocity for one subject. Preceding the initial of arm rise (vertical line a, Fig. 2), the COP moves backward then forwards as the arm is raised. These anticipatory postural adjustments occurring prior to reach onset were consistent across loads and predictability conditions.

As the reaching movement is about to be completed, COP velocity reaches a peak, then decreases shortly before the hand contacts the object (vertical line b, Fig. 2). In the predictable condition (top rows, Fig. 2), the time interval between the peak of COP velocity and contact was longer for heavier than light trials. Conversely, during unpredictable trials this time interval exhibited similar values across all loads (bottom rows, Fig. 2).

Note that during the last segment of the arm movement (from object contact to the end of object lift, lines b and c, respectively, Fig. 2), the COP velocity undergoes several fluctuations but only in the unpredictable conditions.

The three time points indicated by arrows in Fig. 2 were used as temporal landmarks to characterize changes in COP position and velocity with respect to arm movement onset and object contact (Fig. 3A). Object load or predictability condition did not affect the duration of the time intervals between arm movement onset and each of the time points in either predictability condition (top row, Fig. 3A).

A similar behavior was observed regarding intervals between time to object contact and point 1 (left panel, bottom row, Fig. 3A). Conversely, analysis of the time intervals between object contact...
and points 2 and 3 (center and right panels, bottom row, Fig. 3A) indicated a significant effect of load ($p = 0.0095$ for point 2; $p = 0.012$ for point 3) and load $\times$ predictability interaction ($p = 0.018$ for point 2; $p = 0.029$ for point 3) but the main effect of predictability was not significant. These results depended on the different timing data recorded for the three loads during predictable condition. In fact, for the point 2, peak COP velocity preceded object contact during trials with heavy (−15 ms ± 7) and medium loads (−18 ms ± 7) but it occurred after object contact when lifting light load (13 ms ± 11). The main effect of object load on the intervals between object contact and points 2 was statistically significant when the lightest load was compared to the two heavier loads (post hoc: light load vs. medium load, $p = 0.027$; light load vs. heavy load, $p = 0.045$; medium load vs. heavy load, $p = 0.714$).

A similar trend was found for the time interval measured between object contact and point 3: for heavy (37 ms ± 14) and medium loads (41 ms ± 11) the intervals were shorter than light load (72 ms ± 16) (post hoc: light load vs. medium, $p = 0.015$; light load vs. heavy load, $p = 0.043$; medium load vs. heavy load, $p = 0.628$).

It is noteworthy that for unpredictable condition, the average time intervals between the three loads in points 2 and 3 (−17 ms ± 6 and 46 ms ± 12, respectively) were similar to those associated with the two heavier loads in the predictable condition (−17 ms ± 7 for point 2; 40 ms ± 11 for point 3).

The COP moved forward accompanying the hand to grasp and lift the object until the end of arm movement. With respect to COP position at the onset of arm movement, data for predictable and unpredictable conditions converged to a value of −4 mm ± 2 for all loads, showing no statistical difference.

Two-way ANOVA regarding the data illustrated in Fig. 3B indicated a main effect of load for position measured at the object contact ($p = 0.011$) and at the end of movement ($p = 0.006$). A significant effect of load $\times$ predictability interaction was detected only at object contact ($p = 0.017$) and not significant effect of predictability was reported for the values of position measured at the time of object contact or at the time of movement end.

For the predictable condition, the forward path followed by the COP from time point 1 (first COP trajectory change) to the time of object contact was shorter for light than heavier loads (7 mm ± 1 for light, 16 mm ± 2 for medium and 12 mm ± 2 for heavy; left panel of Fig. 3B). Post hoc comparison shows significant differences for the light load vs. medium ($p = 0.018$) and light load vs. heavy load ($p = 0.048$), while medium load vs. heavy load was not significant ($p = 0.137$). For unpredictable trials, COP position at the time of object contact was similar for all loads (14 mm ± 1) and resembled the average value of COP position measured for predictable trials with heavy and medium loads (14 mm ± 1).

At the end of arm movement the COP displacement for light loads was again shorter than for the other loads conditions (Load factor $p = 0.0002$; post hoc: light load vs. medium $p = 0.019$; light load vs. heavy load $p = 0.013$; medium load vs. heavy load $p = 0.022$). However, the difference between the positions associated at each load progressively increased regardless of predictability condition (right panel of Fig. 3B). In fact, no significant effect was detected for predictability and load $\times$ predictability interaction. The similar outcome between predictable and unpredictable conditions at the end of arm movement depended on acquiring sensory information about the mass (unpredictable condition) shortly after object lift onset.
The present study examined anticipatory postural adjustments in a reach-to-lift task involving lifting objects with different masses. We addressed the question of whether the timing and magnitude of APAs occurring before reach onset are modulated to object mass or, conversely, whether such modulation occurs after reach onset but prior to object contact.

We found that both magnitude and timing of APAs were modulated as a function of object load prior to lift rather than at the onset of the reaching movement. As expected, this modulation occurred when subjects could predict, on a trial-to-trial basis, the upcoming load they were about to lift. In contrast, when the effect of lifting the object with different masses could not be accurately predicted, subjects responded with a modulation of the COP position or timing at all loads that resembled that associated with the medium and largest loads.

This finding is reminiscent of anticipatory changes in grasp behavior (grip aperture and trajectories) described by studies of reach-to-grasp in response to visual uncertainty about the hand and object position [6,26]. This similarity suggests task-independent motor control strategies when humans are unable to predict the consequences of motor plans.

The timing and trajectory pattern of COP anticipation relative to the onset of movement reported in this paper are consistent with those reported by other studies of APAs during unloaded arm
raising [4,12,24]. APAs associated with the onset of arm movement are usually scaled according to load [9,29] or other movement parameters, e.g., velocity [15], amplitude [1], and force condition [16]. The absence of effect of load on COP prior to reaching appears to be in contrast with this scenario. However, it should be emphasized that in our experiments modifications of mass conditions occurred some time after arm movement onset, whereas in the cited papers the load changes before [29] or very close to movement onset [9].

The evidence that loads modulated APAs close in time to object contact, agrees with the general view expressed by Massion and reported by several authors (for review see [20]) according to which APAs are strictly related to the timing of focal perturbing movement regardless of other movement parameters. Similarly to the studies on single focal movement, here the information on timing might be provided to APAs process by the segmented programming of reach-to-grasp movements. It is widely accepted that reaching to vs. grasping an object are mediated by separate programs encoding specific sensory-motor parameters [2,23,28]. As the timing and the amplitude of these parameters are responsible for the timing and magnitude of postural perturbation, a possible interpretation of our findings is that these parameters are shared across neural structures responsible for planning limb movement and APAs.

APAs are implemented by the CNS either for predicting the consequences of an action or to prepare to support the focal movement. Here, we can see this last process at work. In fact, the progressive increase of the path length of forward COP as the object mass increases may assist the control of the limb dynamics for lifting the object. This postural behavior has been observed during simple grasp and lift objects of different masses [9] or in subject raising their arm with loaded and unloaded condition [12]. Thus, the control system predicts the necessary postural adjustments while accounting for the time to anticipate the effects of perturbation and the amount of postural changes that are useful to support the focal movement.

The findings of lack of APAs modulation to object load before onset of reaching movement and the occurrence of APAs modulation prior to object contact could result from two, non-mutually exclusive mechanisms or constraints. Specifically, modulating COP to a future event might be more efficient or accurate when timed to temporally close, rather than distant, events. This is because, by allocating APAs to individual sub-tasks, e.g., arm lift and object lift, prediction of the consequences of each sub-task can be implemented on a shorter time scale. This might potentially reduce the computational load as well as risks of prediction errors. At the same time, however, subdividing APAs to each sub-task might appear to be a counter-intuitive finding, as one would have expected a modulation earlier in the task (prior to arm lift) given the predictability of object load that the subject was going to lift. Therefore, our results might also suggest limitations in the predictive capability of the CNS in relation to ‘how far in the future’ it can go when predicting the consequences of planned actions.

Our findings provide insight into anticipatory postural control as a function of multi-segment control, i.e., upper limb. As most of research on APAs has focused on single segment control [17,21,22], the current work extends previous investigations by revealing new control strategies based on temporal segregation of APAs to sub-components of a movement sequence.

Further work is needed to determine whether such segregation is an optimal strategy to minimize prediction errors or it reflects limitations in the extent to which the CNS can predict consequences of planned movements. The latter phenomenon deserves further investigation particularly in clinical populations with impairments in planning movement sequences.

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